UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
Washington, DC 20460

AUTHENTICATION

I, William Charmley, attest that I am the Director, Assessments and Standards Division, Office of Transportation and Air Quality, Office of Air and Radiation of the United States Environmental Protection Agency (EPA or Agency) and that the attached documents are true, correct, and compared copies of the file copies in my legal custody, consisting of:

A 339-page report entitled: [Brake Emissions: Emission Measurements from Brake and Clutch Linings from Selected Mobile Sources]

Subscribed under the penalty of perjury on this __13th___ day of __March___, 2023.

WILLIAM CHARMLEY Digitally signed by WILLIAM CHARMLEY
Date: 2023.03.13 13:02:58 -04'00'

William Charmley, Director
Assessments and Standards Division
Office of Transportation and Air Quality
Office of Air and Radiation

CERTIFICATION OF TRUE COPY

I, Jennifer Clark, certify that I am the Associate General Counsel, General Law Office, Office of General Counsel, of the United States Environmental Protection Agency; that I am the designee of the General Counsel for the purpose of executing certifications under 40 C.F.R. sec. 2.406; that I have duties in Washington, District of Columbia; and that the official whose signature appears above has legal custody pursuant to 40 C.F.R. sec. 2.406 of the original documents, copies of which are attached, as witnessed by my signature and the official seal of the United States Environmental Protection Agency.

Clark, Jennifer Digitally signed by Clark, Jennifer
Date: 2023.03.14 10:59:29
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Jennifer Clark
Associate General Counsel
General Law Office
Office of General Counsel

BRAKE EMISSIONS: EMISSION MEASUREMENTS FROM BRAKE AND CLUTCH LININGS FROM SELECTED MOBILE SOURCES

M. G. Jacko
R. T. DuCharme

FOREWORD

The work described herein, "Emissions Measurements from Powered Brake and Clutch Linings From Selected Mobile Sources," was performed for the Office of Air and Water Programs, Environmental Protection Agency, Ann Arbor, Michigan. This work was carried out under EPA Contract 68-04-0020 from May 10, 1971 to March 31, 1973. The EPA Project Technical Officer was Dr. Joseph H. Somers.

The program was contracted to Bendix Research Laboratories, Southfield, Michigan. The work was performed in the Materials and Processes Department, Dr. William M. Spurgeon, Manager, of the Mechanical Sciences and Controls Laboratory, Mr. L. B. Taplin, Director. The program was under the supervision of the Principal Investigator, Dr. Michael G. Jacko.

Sections 4, 5, and 6 of this report were prepared by Mr. R. T. DuCharme. The data base of Section 10 was prepared by Mr. A. R. Spencer. All other portions were prepared by Dr. Michael G. Jacko.

Other contributors to the program were as follows: Mr. R. D. Stapleton (sample collection, sample processing, calculations, and numerous other tasks); Dr. R. M. Rusnak and Mr. D. G. Jones (microscopy analyses); Mr. L. Smith (vehicle test driving); Mr. H. M. Danbert (vehicle preparation and test driving); Mr. P. R. Stewart (fabrication of collectors); Mr. T. N. Vinson (technical writer); Mr. J. Gulvezan, Mr. A. Tomala, and Mr. W. R. Kee of Machine Systems Department (rotating seals designs), and Mr. C. Cowan and Mr. C. Morton of Bendix Automotive Controls Systems Group (information on vehicle testing and friction materials). Computer programming and processing of computer data were performed by Miss J. Lindsay. Mr. C. L. Gray and Mr. W. H. Houtman of EPA are acknowledged for their suggestions incorporated into the brake emissions collectors.

Special thanks go to Dr. W. M. Spurgeon, Manager of the Materials and Processes Department, for his encouragement and suggestions throughout the program.

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16. Abstracts In order to define the extent of gas and particulate emissions from automotive brakes (and clutches), a combination separation and storage collection system was devised. Unique emissions collectors for both disc and drum brakes and for a clutch were conceived, designed, and built as the main embodiment of this instrumentation. The hardware was installed on a vehicle which was then driven through various test cycles to determine the extent and type of brake emissions generated at low and high operating temperatures. Typical driving conditions, such as the Detroit Traffic Test, as well as more abusive driving conditions such as fade tests, were included. Typical original equipment and aftermarket friction materials for disc and drum brakes were used in the tests. Brake relines were made to simulate typical consumer-type practices. The brake emissions generated were removed from the various collectors and mass balances were performed. The particulates were processed and analyzed by a combination of optical and electron microscopy to ascertain the asbestos content and the asbestos particle size distribution in the wear debris. Comparisons of emissions from new and used friction materials, disc and drum brakes, and original equipment and aftermarket materials were made. Finally, an estimate was made of the total emission of asbestos by all of the vehicles in the country.

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ABSTRACT

In order to define the extent of gas and particulate emissions from automotive brakes (and clutches), a combination separation and storage collection system was devised. Unique emissions collectors for both disc and drum brakes and for a clutch were conceived, designed, and built as the main embodiment of this instrumentation. The hardware was installed on a vehicle which was then driven through various test cycles to determine the extent and type of brake emissions generated at low and high operating temperatures. Typical driving conditions, such as the Detroit Traffic Test, as well as more abusive driving conditions such as fade tests, were included.

Typical original equipment and aftermarket friction materials for ~~both~~ disc and drum brakes were used in the tests. Brake relines were made to simulate typical consumer-type practices. The brake emissions generated were removed from the various collectors and mass balances were performed. The particulates were processed and analyzed by a combination of optical and electron microscopy to ascertain the asbestos content and the asbestos particle size distribution in the wear debris. Comparisons of emissions from new and used friction materials, disc and drum brakes, and original equipment and aftermarket materials were made. Finally, an estimate was made of the total emission of asbestos by all of the vehicles in the country: on the average, more than 99.7 percent of the asbestos is converted; the contribution to the atmosphere is 5060 pounds, or 3.2 percent of the total asbestos emissions.

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SECTION 1

INTRODUCTION AND BRIEF SUMMARY

The chrysotile form of asbestos is a major constituent in automotive brake linings and disc pads, and in the friction materials used in clutches. These components are expendable. In typical passenger car service, drum linings wear out in about 40,000 miles, disc pads in about 30,000 miles, and clutch facings in about 70,000 miles. There are, of course, wide variations in the service lives of these components, which depend on the nature of the friction materials used, on driver habits, and on driving conditions.

The expendable members of the common automotive friction couples contain not only asbestos, but also various organic and inorganic friction and property modifiers. These constituents are bound together by phenolic resins. Because of their high content of organic substances, such friction materials are classified as "organic." Asbestos-free friction materials with a high content of metallic substances are classified as "semi-metallic." Over 99 percent of the automotive friction materials used today are organics.

The mechanisms by which organic friction materials wear can be classified under five headings: thermal, abrasive, adhesive, macroshear, and fatigue. Thermal, abrasive, and adhesive wear are considered to be the most important mechanisms, thermal wear predominating above 450°F, abrasive and adhesive wear predominating below 450°F (the temperature being measured by a thermocouple in the rotor, about 0.050 inch from the sliding interface). The organic constituents pyrolyze or oxidize, and are emitted to the air as carbonaceous solid particles or gaseous reaction products. The asbestos fibers are pulverized into small particles which are trapped in the brake (or clutch) housing, or fall to the road, or are emitted to the air. Disc brakes do not trap as much as drum brakes. Most of the asbestos is heated to temperatures high enough to cause chemical conversion, and is therefore trapped or emitted as olivine or forsterite particles.

When the large number of existing cars and trucks is considered, each with eight or more pieces of friction material in the brake system, plus more in the clutch mechanism, it becomes apparent that an air pollution problem may exist. Considered in another light, there are perhaps one billion pieces of friction material in vehicles in the United States, gradually being pyrolyzed and ground to dust. The brake systems in the vehicles utilizing these friction materials can thus be considered as chemical reactors, each emitting organic and inorganic compounds, including asbestos and its decomposition products, to the atmosphere. The compositions of the gaseous and solid emissions have not been well known, and the particle sizes and shapes of the solid emissions have not been well known. Because of the possible damage which these emissions can produce in human respiratory systems, it is desirable to identify and quantify them, with particular regard to asbestos. That is the purpose of the program described in this report.

The amount of asbestos emitted is a function of many variables:

the number of vehicles on the road,

the number of miles driven per year by each,

vehicle size,

the number of vehicles using manual clutches,

conditions of driving (city, expressway, mountain; driver habits, etc.),

brake system design, and

brake type (drum or disc),

rotor condition (surface roughness, scoring, cracking, pitting, etc.),

rotor design (e.g., solid or ventilated discs, finned drums, etc.),

rotor metallurgy (cast iron or aluminum),

volume percent of asbestos in the friction material, and

inherent wear resistance of the friction material.

In this program a passenger car of medium weight (test weight: 4800 pounds), produced in high volume, was used. It was equipped with a manual transmission and clutch, ventilated cast iron disc brakes on the front, and standard cast iron drum brakes on the rear.

A passenger car was selected for testing because of the following factors:

(1) vehicle braking cannot be simulated realistically on small-scale friction test-machines with the present state of the art;

(2) full-scale brake and clutch dynamometers provide fairly good simulation, and can be used for checking out the emissions collection system; separate tests for brakes and clutches would be required, however, thus increasing program costs, whereas on the vehicle, disc and drum brakes and clutches can be tested simultaneously;

(3) air flow in the dynamometers differs from that in vehicles, and emissions from drum brakes will therefore be different in the two cases.

Three series of tests were run, using friction materials as tabulated below:

Vehicle Test	Simulation	Friction Materials	Remarks
1	Original Equipment	OEM[1] Disc Front OEM Drum Rear	Class A organic disc pads
2	Partial Reline	AM[2] Disc Front Used OEM Drum Rears	No metallic chips; Discs and drums not turned
3	Full Reline	AM Disc Front AM Drum Rear	Disc pads and secondaries contain brass chips Discs and drums turned

This selection has several features. It provides a replication of one test, thus giving an estimate of repeatability. It includes a primary/secondary combination that serves both OEM and aftermarkets. It includes one combination (two materials) of widely used OEM materials. It includes one combination (two materials) from one of the larger aftermarket suppliers. It includes a set of used linings (about 3,000 miles) to give data on the emissions at various stages of lining life. It includes two different disc pad materials from two of the larger aftermarket suppliers. Five different manufacturers were represented in the friction material selections.

The collection of particulate and gaseous emissions from any vehicle friction couple has never before, to the authors' knowledge, been reported in the literature. To define the extent of these emissions, a combination separation and storage collection system was devised. Unique emissions collectors for both disc and drum brakes, and for a clutch, were conceived, designed, and built as the main embodiment of this instrumentation. The collectors separated the wear debris into three different fractions: a sump sample which included the wear debris on the lining surfaces, in the rivet holes, and on the brake drum; a surfaces sample which included the wear debris on the brake and collector shroud surfaces; and an airborne sample collected on membrane filters.

The vehicle was equipped with standard brake test instrumentation. A front disc brake collector and a rear drum brake collector were installed on the right side of the vehicle. The clutch was sealed by closing the

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[1]OEM - Original Equipment Manufacturers
[2]AM - aftermarket

holes in its casing. The left wheel brakes were left in their normal configuration and were used to monitor the operation of the shrouded brakes. Wear debris was also taken from the left brakes; the amounts of debris collected and its composition were used to demonstrate that the brake shrouding did not significantly affect the operation of the brakes within the emissions collectors.

Although there are many acceptable original equipment manufacturers' brake and friction material tests for measuring a specific collection or combination of collections, no one test adequately matches driving conditions which would be representative of all vehicles. Consequently, it became necessary to devise a rational and meaningful vehicle test. A total of seven schedules were chosen and each was followed by a measurements procedure (take emissions samples, measure wear, inspect systems, and replace worn parts). The first three schedules - Burnish, After Burnish (A.B.) Baseline, and Detroit Traffic - Represented low-temperature testing. The final four schedules - 10-Stop Fade, After Fade (A.F.) Baseline, 15-Stop Fade, and Final Baseline - represented high-temperature and abrusive testing.

The mileage accumulations for each schedule of each vehicle test verified the possible test mileage reproducibility. A critical component of the front disc brake collector was a unique rotating seal. For the 8100 miles of testing, only eight rotating seals were required — an exceptional improvement over the anticipated need at the start of the program.

Prior to vehicle test 1, a Burnish schedule was performed and the temperatures for the right front disc brake were found to be near 400°F. The temperature difference, ΔT, between the right and left front brakes ranged from 200 to 250°F. This was unacceptable. The addition of several thermal control aids reduced the ΔT to a range of 115 to 160°F. Most important was the reduction of the right front brake operating temperature from about 400°F to about 300°F. The brake shrouding did not present any problems on hot days. During the Detroit Traffic Test, the ΔT between the front brakes remained between 100 and 140°F while that for the rear drum brake remained between 10 and 30°F.

The range of asbestos content in the brake emissions for vehicle tests 1 and 2 went from a high of 1.65 percent to a low of 0.03 percent for the 90 analyses; only three were above 1.00 percent. The overall average for vehicle test 1 was 0.40 percent and for vehicle test 2 was 0.25 percent. For vehicle test 3, the range of asbestos content was from a high of 0.51 percent to a low of 0.003 percent. The overall average was 0.07 percent. In this work, all values for heavy-duty (abusive) braking were less than one percent, which is significantly less than the 15 percent asbestos content reported by Lynch of the U.S. Public Health Service.

To provide a systematic, independent check on the asbestos analyses, the EPA Project Officer arranged a second contract for Battelle Columbus Laboratories to analyze twenty-four samples generated by Bendix Research

Laboratories. Johns-Manville also provided three analyses. The Johns-Manville and Battelle data agreed very well. In 19 of the 24 analyses, the Bendix results were slightly higher than the corresponding Battelle results. The Bendix average was 0.25 percent, while the Battelle average was 0.17 percent, or 68 percent of the Bendix average. The Bendix data were expected to be higher for the following reasons: all fibers found were assumed to be cylinders of projected diameter and length, and a fiber with an elliptical cross section was actually smaller in volume than reported; and all fibers were assumed to be pure asbestos, (partially degraded asbestos or olivine fibers were mechanically reduced to non-fibrous material by the other analytical techniques, so only the stronger asbestos fibrils that remained were counted).

Analysis of the gaseous emissions was made difficult by the large quantities of water and carbon dioxide which by-passed the gas conditioning trap and entered through the rotating seals. Most samples showed traces of C_1 to C_3 hydrocarbons only as lower concentrations of higher molecular weight gases could not be detected. When the gases were concentrated from the fade tests, C_4 to C_8 compounds such as butanes, benzene, toluene, phenol, and cresols were detected in the gas traps. The corresponding shroud extracts showed C_{12} to C_{30} materials, including cardanol.

To compare the generation of asbestos emissions properly, it was found necessary to calculate the emissions factors for each sample in micrograms/mile (μg/mile). These values were obtained by multiplying the weight of generated brake debris by the appropriate asbestos percent, followed by dividing by the miles per test schedule. Thus, either a high asbestos content or a large sample gave a high factor.

The following observations were made:

- Asbestos emissions were higher for new friction surfaces and decreased with use.
- Initially the drum brake produced more asbestos emissions than the disc brake. The difference decreased as the materials continued to be used.
- Heavy (abusive) duty did not necessarily give a higher percent asbestos, however, the large amount of debris produced gave a significant rise in asbestos emissions.
- The order of decreasing asbestos emissions from brakes was found to be:

Fade or heavy-duty stops	Decreased asbestos emissions ↓
Burnish	
Moderate braking	

- For the disc pads only, there was an increase in asbestos emissions with increased asbestos content in the friction material (there was no such trend for the drum brake materials).
- Both the front disc pads and the drum linings of vehicle test 3 had wear comparable to that of the other two vehicle tests, yet the asbestos emissions were significantly lower. Both pads and linings contained brass chips which may have been in part responsible for the more complete conversion of the asbestos in the brake emissions, possibly because of better heat transfer to the asbestos.
- For both disc and drum brakes, the surfaces sample was the largest of the three (∿92 percent), the sump sample was next (∿7 percent), and the airborne sample was the smallest (∿1 percent).

Two series of weighting factors were developed. The distribution weighting factors were calculated from the material recoveries in the shrouded and unshrouded brakes as indicated earlier. Estimates were made for both disc and drum brakes from the test vehicle for the amounts of the different samples distributed from the brakes. These estimates were made for the Burnish schedule, for the end of a complete vehicle test, and for the end of all three vehicle tests. For the drum brake, estimates were made up to 40,000 miles. The severity weighting factors were calculated from the percentages of different braking modes: for new versus burnished friction materials, for severe (or abusive) versus moderate braking, and for the renewal of friction surfaces (A.F. Baseline).

The total asbestos emissions estimate for the test vehicle was calculated from the asbestos emissions factors and the severity weighting factors. The average asbestos emissions factor for the disc brakes, drum brakes, and clutch were used along with the Burnish (new surfaces), A. B. Baseline (surface preparation), Detroit Traffic (moderate braking), 10-Stop Fade (severe braking) and A. F. Baseline (surface renewal) weighting factors. The value obtained for the test vehicle was 28.51 μg/mile.

The fate of the asbestos emissions was calculated with the use of the distribution weighting factors as follows:

Road Drop-out	81.9%
Airborne:	3.7%
Brake Retention:	14.4%

The annual total asbestos emissions estimate for 96,400,000 passenger vehicles travelling an average of 9,978 miles per year was found to be 60,400 pounds, distributed as follows:

Road Drop-out:	49,470 lbs
Airborne:	2,230 lbs
Brake Retention:	8,700 lbs
	60,400 lbs

The annual total asbestos emissions estimates for light trucks, medium trucks (and buses), and heavy trucks were found to be:

Light trucks	32,300 lbs
Medium trucks (and buses)	16,300 lbs
Heavy trucks	22,900 lbs
	81,500 lbs

The distribution of the total asbestos emissions estimate for trucks was calculated to be as follows:

Road Drop-Out:	87.9%
Airborne:	2.9%
Brake Retention:	9.2%

The estimated asbestos emissions for all vehicles in pounds/year is summarized as follows:

	Total Asbestos Emissions (lbs)	Distribution (lbs)		
		Drop-Out	Airborne	Retention
Passenger Cars	60,400	49,470	2,230	8,700
Light Trucks	32,300	28,420	940	2,940
Medium Trucks (and buses)	16,300	14,330	470	1,500
Heavy Trucks	32,900	28,920	950	3,030
Miscellaneous (motorcycles, trailers, etc.)	16,300	14,330	470	1,500
	158,200	135,470	5,060	17,670
Distribution by percent:		85.6%	3.2%	11.2%

These estimates are considered to be maximum values.

SECTION 2

OBJECTIVES AND BACKGROUND

2.1 OBJECTIVES

2.1.1 Objectives of this Program

The objectives of this program, as stated in the Request for Proposal and in the Contract, were as follows:

> "In order to define the extent of non-engine asbestos emissions, the Office of Air Programs of the Environmental Protection Agency is seeking the assessment of these emissions on a single vehicle basis. The efforts are to include emissions measurements from several different types of brakes as well as a clutch assembly. The end objective of the work will be the documentation of these emissions to assess their overall contribution to the atmosphere."

2.1.2 Bendix Technical Approach

2.1.2.1 Select Suitable Vehicle and Friction Materials

For the results to be representative of the average consumer-type vehicle usage, it was necessary to select a vehicle intermediate between the compacts and luxury vehicles. Moreoever, it was desirable to select a vehicle with original-equipment friction materials, produced by more than one supplier, and equipped with a clutch. Aftermarket friction materials, produced by several manufacturers, were also selected.

2.1.2.2 Conceive, Design, and Build Brake and Clutch Emissions Collectors

Since only 100-percent collection could give a mass balance, it was necessary to conceive, design, and build brake and clutch emissions collectors which could collect all the emissions and differentiate among wear debris remaining on the friction materials, debris remaining on the local surfaces of the foundation brakes, and debris entering the atmosphere. Moreoever, provision was necessary for the collection and storage of gaseous decomposition products.

2.1.2.3 Test a Typical Collector and Instrument the Vehicle

To ensure that the concepts and hardware were technically sound, it was necessary to install the most critical collector on an inertial dynamometer to verify its operation. Once proven, that collector and the others, along with brake test instrumentation, could be installed on the vehicle.

2.1.2.4 Select and Run Suitable Driving Test Schedules

Because of the wide variety of driving which takes place throughout the various regions of the country, it was necessary to select a vehicle test program in which brake emissions could be collected for new brake linings and rotor combinations. The program included typical consumer-type driving on flat terrain, and heavier-duty braking as encountered in hilly areas.

2.1.2.5 Collect and Analyze Emissions

As the main goals were to determine the asbestos content of the emissions and their particle-size distributions, it was necessary to select an analytical method which would not disturb the particle size distribution and yet be sensitive to very small amounts of asbestos. Further, it was necessary to collect and separate very low concentrations of gaseous emissions from extremely large quantities of air and other molecules present in large concentrations.

2.1.2.6 Estimate Asbestos Emissions for Cars and Trucks

Because of funding and time limitations, only a few selected tests could be run. Based on the measurements taken and a knowledge of the overall vehicle population, it was possible to prepare estimates for total emissions from cars and trucks operating in the United States.

2.2 PRIOR WORK

2.2.1 Published Data

The only known published data on asbestos emissions were those reported by Jermiah Lynch of the U.S. Public Health Service, Department of Health, Education, and Welfare.[(2-1)*]

The paper discusses tests which were performed with brake test machines, using one-inch-square samples, and tests performed on an inertial dynamometer where a complete brake and clutch were used. Emissions samples were collected on membrane filters and analyzed by electron microscopy. In all but a few tests, the drum brake linings showed less than 1 percent free fiber in the decomposition product. In some tests reported, where the lining temperatures were extremely high and accompanied by a rapid drop in coefficient of friction (fade), a significant mass of free fiber was released - approximately 10 to 15 percent. The clutch test gave no asbestos fiber.

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*Numbers in parentheses designate References at end of section.

2.2.2 Unpublished Data

At the time of writing of this report, there were three known works which had been completed or were in progress. The amount of brake wear debris and its composition were determined on a full-brake inertial dynamometer using a duo-servo drum brake in 1968-69.[2-2] The determination of the amount of asbestos in airborne brake debris sampled downwind of a disc brake installed on an inertial dynamometer was in progress.[2-3] The determination of asbestos content in airborne brake debris sampled downwind of vehicle-mounted disc and drum brakes was also in progress.[2-4]

2.3 BACKGROUND

2.3.1 Energy Absorption by Friction Materials

2.3.1.1 Brakes

During a stop, the automobile brake converts the kinetic energy of the moving vehicle into heat, absorbs the heat, and gradually dissipates it to the atmosphere. The sliding friction couple in the brake consists of a cast-iron rotor (drum or disc) and a stator on which is mounted a friction material or lining consisting of asbestos fiber, property modifiers, and an organic resin binder. Lining is considered expendable. Over a long period of time and many miles of service, much of it is converted to dust and gases. Smaller amounts of the rotor are also converted to wear debris. Particulate debris is partially retained and partially emitted from the vehicle in normal service.

2.3.1.2 Clutches

The "manual" automobile clutch transfers the kinetic energy of the engines rotating crankshaft smoothly to the transmission and wheels. Any slippage results in generation of heat, which is absorbed and eventually dissipated to the atmosphere by the clutch. Thus the clutch is basically a dry-running static friction couple (which slides momentarily during gear shifts). The mating materials are usually cast-iron or steel and a friction material or lining which is frequently organic-bound. Organic-bound friction materials consist of asbestos fiber reinforcement, property modifiers, and an organic resin binder. The composition is qualitatively similar to that of brake linings. Clutch linings are also expendable, gradually wearing away in use. The wear debris can escape from manual clutches. Wear debris from friction materials in automatic transmissions is retained almost completely in the transmission fluid.

2.3.2 Compositions of Friction Materials

2.3.2.1 Generalized Classifications

Table 2-1 gives typical compositions of drum lining, disc pad,[2-5] and clutch facing friction materials. The foundation, or major constituent, of practically all organic friction materials is asbestos fiber. Asbestos is chosen because of its thermal stability, its relatively high friction level, and its reinforcing properties. Since asbestos alone does not offer all of the desired friction properties, other materials called friction modifiers are added. Modifiers are varied in type and content to provide desired levels of effectiveness, wear, fade, recovery, and noise. A resin binder is also added to hold the other materials together with adequate strength.

2.3.2.2 Asbestos

The asbestos usually used in friction materials is chrysotile from Quebec or Vermont. Chrysotile, the principal mineral of the serpentine group, has the approximate composition formula

$$Mg_3(Si_2O_5)(OH)_4 \quad \text{or} \quad 3MgO \cdot 2SiO_2 \cdot 2H_2O$$

Table 2-1 - Composition of Typical Automotive Friction Materials (Volume Percent)

	Drum Linings		Disc Pads		Woven Clutch Facings	
	Primary	Secondary	Class A Standard	Class B Heavy-Duty	Standard	Heavy-Duty
Resin Binder	20-30	25-35	18-22	15-18	20-30	15-25
Asbestos Reinforcement	Major	Major	Major	Major	Major	Major
Friction Modifiers						
• Organic						
Friction Dust	10-15	5-15	20-25	0-15		
Elastomer		5-15	10-15	0-10		
• Inorganic						
Carbons/Graphites			1-2	2-15		
Zinc Chips			1-2			
Oxides		0-5		2-7	0-5	0-5
Copper/Brass		0-5		5-10	0-5	5-10
Misc. Inorganics		5-10	0-5	5-15	5-10	5-10
Sulfur					2-5	2-5

P-82-9903

Structurally, it is a pseudohexagonal network of SiO_4 tetrahedra forming a sheet in which all the tetrahedra point one way. A layer of brucite, $Mg(OH)_2$, is joined to the SiO_4 network in such a way that, on one side, two out of every three hydroxyls are replaced by oxygens at the apices of the tetrahedra (Figure 2-1). The macromolecule consists of parallel sheets of brucite-silica layers structured in cylindrical lattices involving closed concentric cylinders, spirals, and sometimes helical arrangements.(2-6)

Bendix Research Laboratories' scientists have been studying asbestos for several years. Figure 2-2 presents the results of differential thermal analysis (DTA) and thermogravimetric analysis (TGA) studies for a common short-fiber grade of chrysotile asbestos.(2-7) The transition at approximately 700°F (370°C), in both the DTA and the TGA thermograms represents the dehydration of the brucite (magnesium hydroxide), the 1.4 percent weight loss corresponding to an approximate concentration of 4.5 percent brucite. The transition at 1250°F (680°C) in both thermograms represents the major dehydroxylation reaction in chrysotile asbestos. At 1580°F (860°C), a sharp exotherm, not associated with any weight change, represents the conversion of the dehydroxylated chrysotile to forsterite ($2MgO \cdot SiO_2$) or olivine [$2(Mg_{1.00-x}Fe_x)O \cdot SiO_2$, where x is approximately 0.02 to 0.16]. TGA results for the asbestos were identical in air and in nitrogen.

Figure 2-3 shows the X-ray diffraction patterns for asbestos heated to different temperatures.(2-8) The crystal structure changes from chrysotile to forsterite (olivine) between 600 and 800°C.

Asbestos fibers are present in greater concentration (by volume percent) than any other ingredient in friction materials. As a consequence, both the relative concentration and the type of asbestos used (with respect to fiber length and "openness" or absorptiveness) significantly affect the amount of resin binder required and the processing and performance characteristics.

2.3.2.3 Resin Binders

Synthetic resins, such as phenolics and modified phenolics, are commonly used as friction material binders. They are prepared as the condensation product between the appropriate phenol (sometimes modified) and formaldehyde in the presence of an acidic catalyst to yield the novolak. When mixed with an appropriate curing agent, they polymerize at elevated temperatures to an insoluble, infusible mass. Other resin systems in wide use are based on elastomers, drying oils, or combinations.

2.3.2.4 Property Modifiers

Friction modifiers can in general, be divided into two classes: non-abrasive and abrasive.(2-9) Organic materials are generally less abrasive than inorganic as described below.

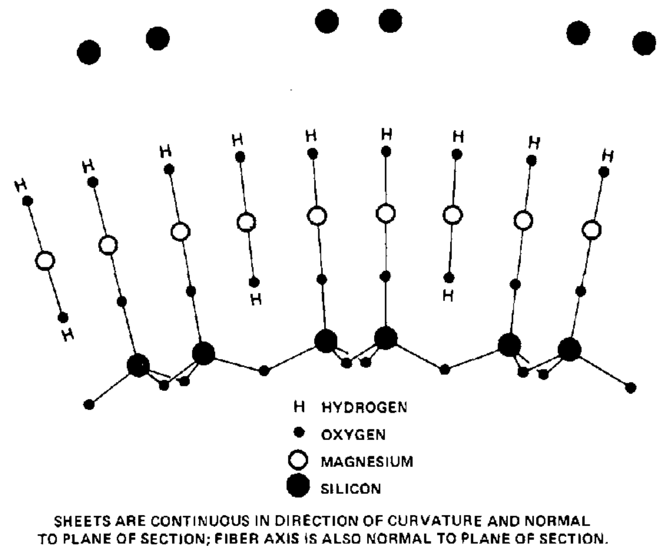

Figure 2-1 - Schematic Structure of Chrysotile Asbestos

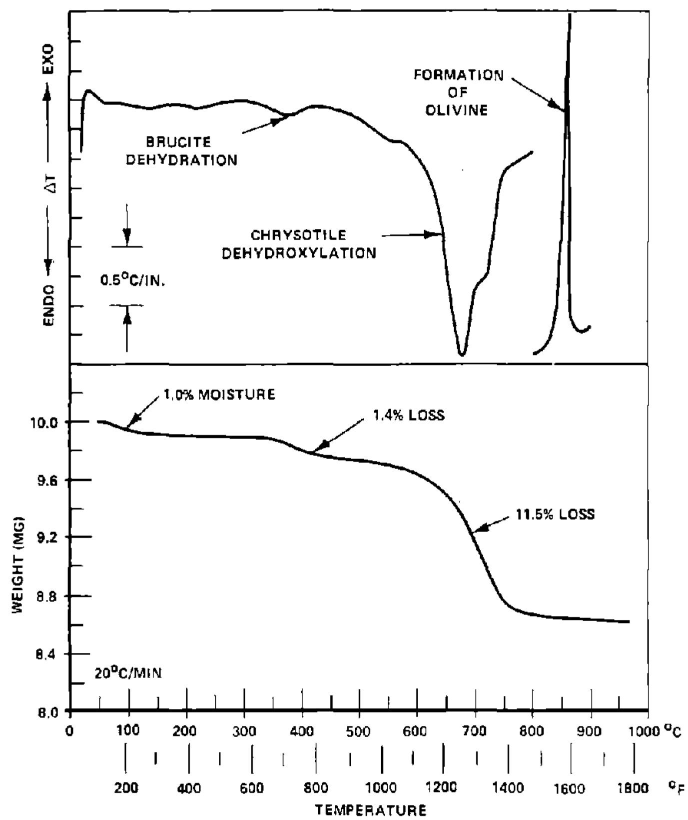

Figure 2-2 - DTA and TGA Thermograms for Chrysotile Asbestos (Bendix Data)

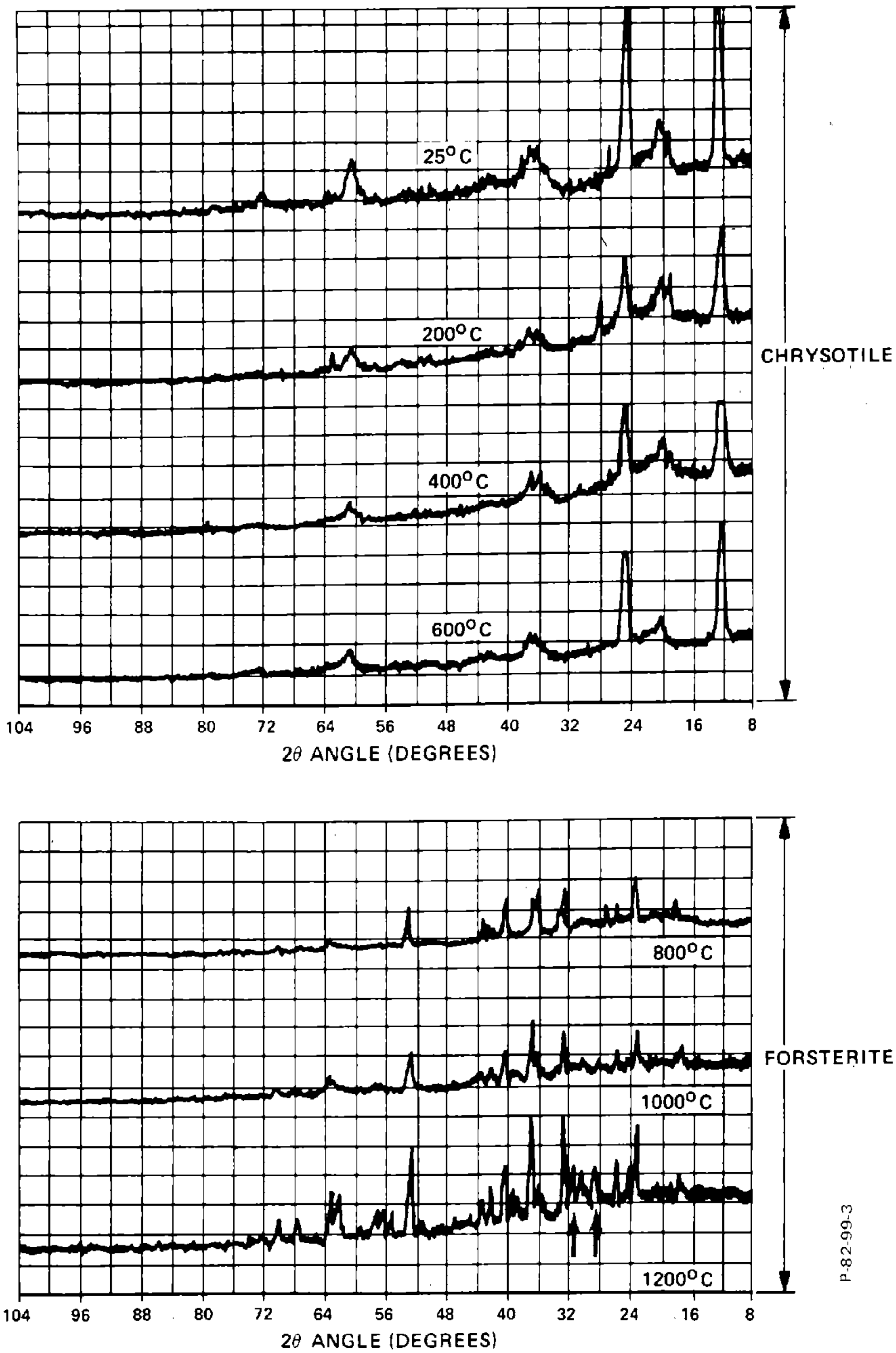

Figure 2-3 - X-Ray Diffraction Pattern of Heated Chrysotile Asbestos (Bendix Data)

2.3.2.4.1 Non-Abrasive Modifiers

Nonabrasive friction modifiers can be classified further as low friction and high friction. The most common and best known of the high-friction materials is known as friction dust. This is a cured resinous material. The most frequently used variety is derived from cured or polymerized cashew-nut-shell liquid, chemically a phenolic compound. When heated with hardening agents, such as hexamethylenetetramine or formaldehyde, it becomes sufficiently hard or polymerized to be granulated. Many other cured resinous or polymeric materials, some with fillers, are also used. Certain friction dusts are combinations of these materials and cashew resin. Ground rubber is normally used in particle sizes similar to, or slightly coarser than, those of the cashew friction dusts for noise, wear, and abrasion control.

Carbon black, graphite, petroleum coke flour, or other carbonaceous materials may also be added as friction modifiers to lower the friction coefficient or to reduce noise. These materials are normally used in the form of fine powders or particles, although graphite is sometimes used in coarse particles or pellets. The amount of friction modifier added is dependent upon the properties desired in the final composite.

2.3.2.4.2 Abrasive Modifiers

Abrasive modifiers, such as alumina and the silicas, are usually used in relatively small amounts and only in very fine particle sizes (generally 100 mesh or finer). Particle size is limited by the fact that large particles of such hard materials would groove and wear the mating surfaces. Minerals are generally added to improve wear resistance at minimum cost. Those most commonly used are ground limestone (whiting) and barytes (barium sulphate), though various types of clay, finely divided silicas, and other inexpensive or abundant inorganic powders may also perform this function. Such materials are inorganic in nature and tend to detract from noise properties and mating surface compatibility.

Metals or metal oxides may also be added to perform specific functions. Brass chips are frequently found in heavy-duty friction materials where, as scavengers, they break up undesirable surface films. Zinc and aluminum are also used. Zinc chips, in relatively small amounts, can contribute significantly to recovery of normal performance following fade.

2.3.3 Friction Material Reactions

2.3.3.1 Absorption and Conversion of Energy

The automobile brake converts the kinetic energy of the moving vehicle into heat, absorbs the heat, and eventually dissipates it to the atmosphere. The clutch absorbs the friction energy generated when the transmission and drive-shaft are engaged or disengaged on manual transmission vehicles. Phenolic-bound brake lining compositions containing asbestos serve as one of the best classes of low-cost expendable members of the friction couple for all-around performance. At low energy absorption rates, the temperature of the friction material, approximately 40 mils from the interface, may rise to 300°F; the interface itself is hotter. Most of the heat is removed from the interface by convection and conduction.[2-10] At high energy absorption rates, heat is generated faster than it can be dissipated and the temperature at the sliding interface reaches a point where chemical reactions occur rapidly. Surface temperatures up to 1600°F have been observed or calculated; the presence of olivine in the wear debris confirms that such temperatures have been reached.

2.3.3.2 Physical and Chemical Changes in Linings During Use

Figure 2-4 illustrates the heterogenous nature of a typical friction material composed of the following ingredients: phenolic binder (30 volume percent), asbestos fiber (55 volume percent), and cashew friction modifier (15 volume percent).

As a result of the energy conversion at the stator-rotor interface, the composition of the brake lining surface is altered. At low service temperatures, the phenolic resin and organic friction modifier convert, on the surface, to compositions with slightly higher carbon/oxygen ratios. At somewhat higher use temperatures, the resin and organic friction modifier convert to carbon more readily, and this in turn oxidizes to carbon dioxide. At the same time, the asbestos wears away more rapidly because of the reduced binder strength and volume at the surface. Figure 2-5 is a photomicrograph of typical wear debris collected from Bendix Research Laboratories' dynamometer, operated at 600°F. Asbestos fibers are prevalent in several of the wear debris particles. Figure 2-6 is a photograph of the improved wear debris collector designed and built for friction and wear research.[2-11] At still higher temperatures, the asbestos converts from its fibrous form to an olivine powder with little or no reinforcing value. Figure 2-7 shows the frictional-heat-affected layer of lining which had experienced more than 10 successive stops from 100 mph without sufficient cooling between stops.[2-12] (A large piece of material is about to separate from this sliding interface - an example of macroshear wear, described later.)

When heat is generated at the sliding interface between stator and rotor much faster than it can be dissipated, the temperature rises and may reach a point where the lining or pad components decompose, oxidize, or melt. The stator material then wears rapidly and the friction coefficient, μ, may decrease. This is fade. Fade has been attributed by some to evolution of gas at the sliding interface; on heating, the gas expands and exerts a force on the lining or pad, tending to push it away from the rotor.[2-13] Fade can generally be ascribed to the formation of a gaseous, a liquid, or a low-friction solid phase at the interface, or to some combination of these phenomena. Figure 2-8

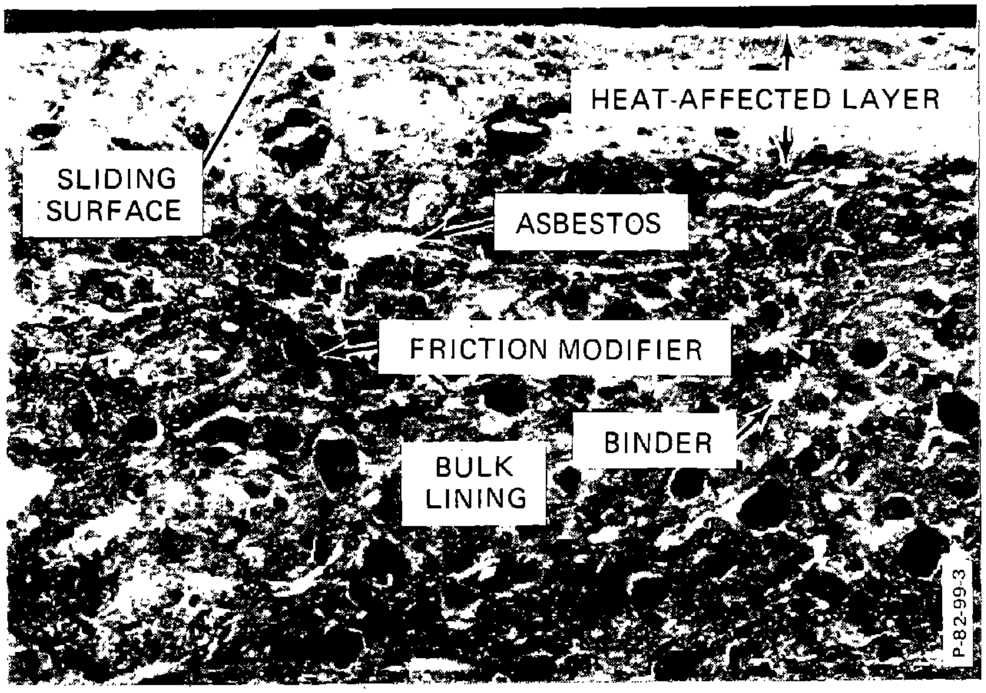

Figure 2-4 - Photomicrograph of Brake Lining Cross Section After 8550 Miles of Test-Track Service

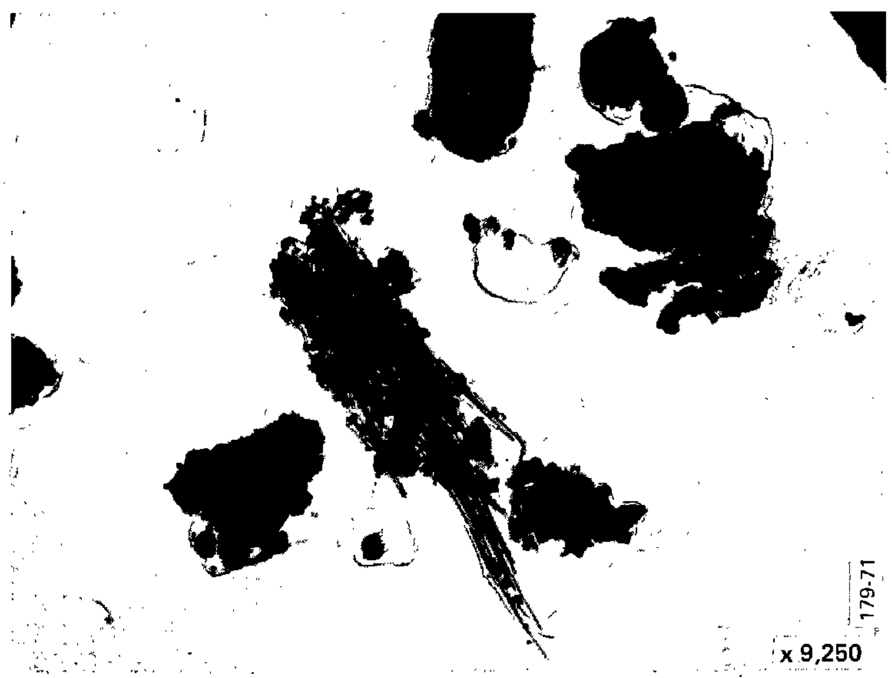

Figure 2-5 - Electron Micrograph of Friction Material Wear Debris (Made during 1966 studies) - 10,000 X

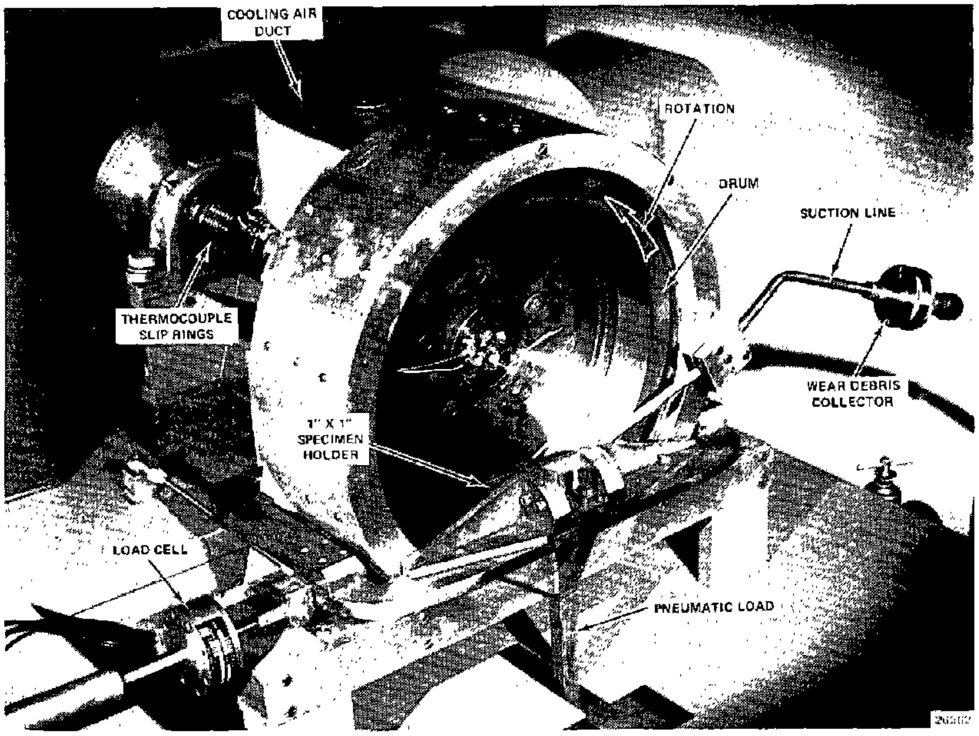

Figure 2-6 - Close-up View of Bendix Drag Dynamometer Showing Wear Debris Collector

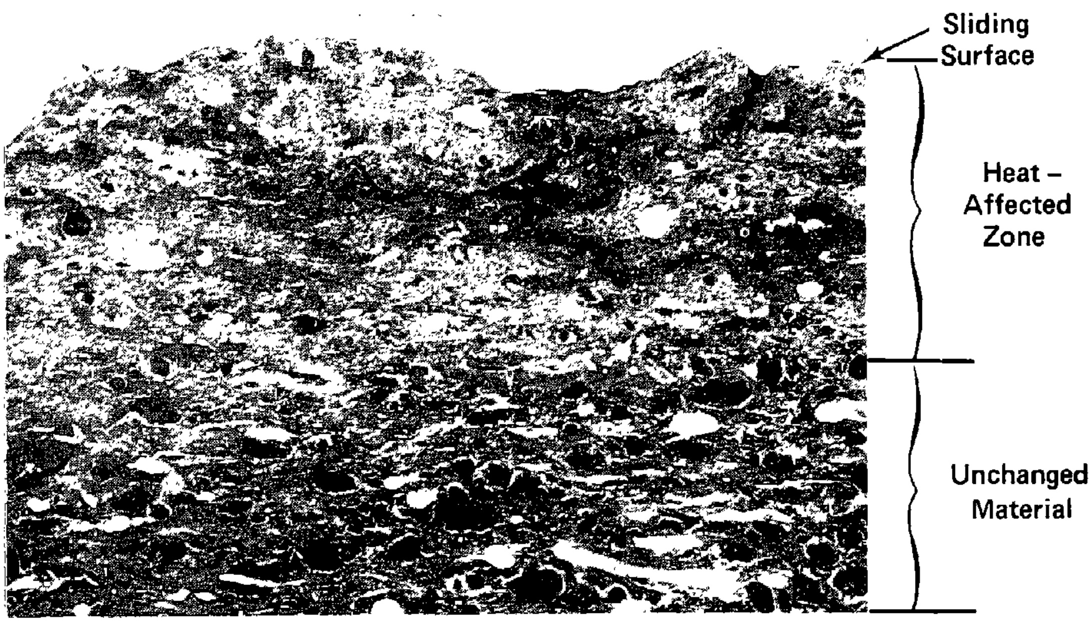

Figure 2-7 - Photomicrograph of Cross Section of Friction Material Test Specimen After More Than 10 Successive Stops from 100 mph on Bendix Full-Brake Dynamometer

PHYSICAL OR CHEMICAL CHANGE	TEMPERATURE °F	°C
CAST IRON MELTS	2105	1150
$CaCO_3$ (CALCITE) DECOMPOSES	1640	895
$CaCO_3$ (ARAGONITE) DECOMPOSES	1520	825
ASBESTOS PRODUCTS TRANSFORM TO OLIVINE	1520	825
ASBESTOS LOSES MORE WATER	1170	630
IRON POWDER AND FIBERS BEGIN OXIDIZING	850	454
GRAPHITE BEGINS OXIDIZING	930	500
ZINC MELTS	787	419
PHENOLIC RESINS CHAR	715	380
PHENOLIC RESINS OXIDIZE	715	380
AMORPHOUS CARBON BEGINS OXIDIZING	700	372
ASBESTOS LOSES WATER	698	370
FRICTION DUSTS AND RUBBER CHAR	500	260
BRASS BEGINS OXIDIZING	>440	>225
ZINC BEGINS RAPID OXIDIZING	<440	<225
FRICTION DUSTS AND RUBBER OXIDIZE	395	200

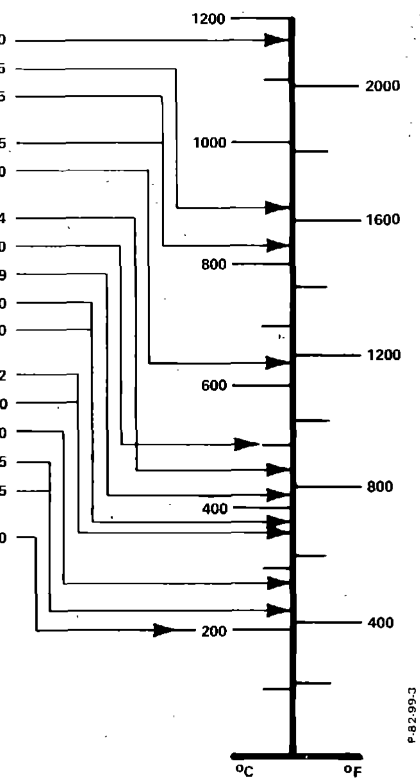

Figure 2-8 - Changes Occurring in the Friction Material as the Temperature Rises

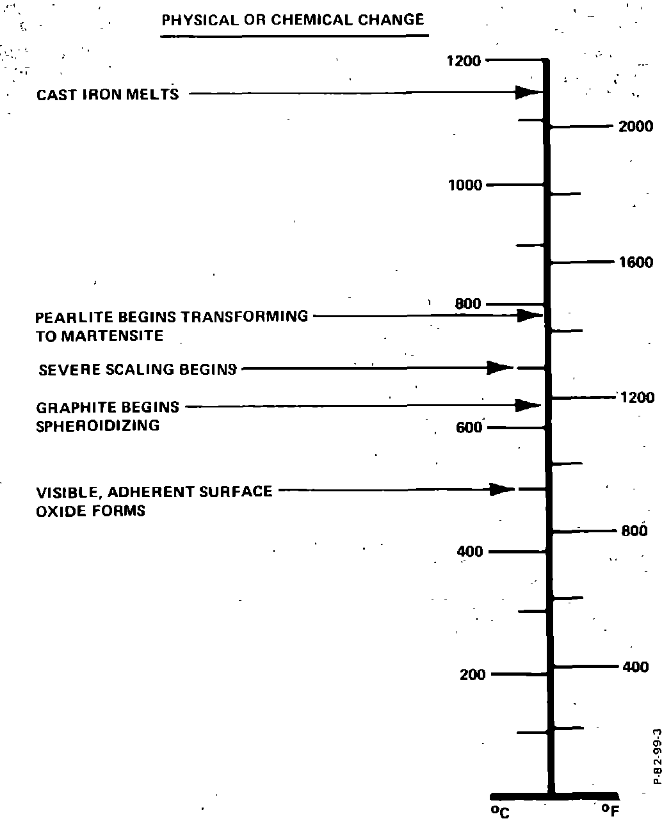

Figure 2-9 - Changes Occurring in the Rotor as the Temperature Rises summarizes the physical and chemical changes which take place in the friction material as the temperature rises.[2-14] Figure 2-9 summarizes the physical and chemical changes which take place in the cast-iron rotor as the temperature rises.

2.3.4 Brake Lining Wear Mechanisms and Generation of Emissions

2.3.4.1 Types of Wear Mechanisms

Emissions are generated by wear. To the consumer, wear is an economic consideration. To the environmentalist, these emissions are substances to be characterized and, if harmful, to be eliminated.

From the basic friction material engineering standpoint, wear resistance is inversely related to friction level and other desirable performance characteristics. Linings with faster wear rate and more frequent surface renewal generally have greater frictional stability. This circumstance is used to advantage in the development of primary-type linings for duo-servo brakes, where, because of design, the stability of frictional properties is of greater significance to brake performance than is wear resistance; use of primary linings with too much wear resistance results in poor fade resistance, less frictional stability, and generally poor overall performance.

Except in the case of primary linings, however, one of the formulator's objectives must be to achieve the highest possible level of wear resistance. Contrary to the opinion of some, maximum life does not require a friction material of maximum physical hardness. What is desirable is a minimum wear rate in normal low-temperature use, a moderately increased rate at elevated temperatures, and a return to the original low-temperature wear rates after being subjected to elevated temperatures.

Total emissions generation may be defined as the sum total of the losses associated with five basic types of wear.[2-15]

- abrasive wear,
- thermal wear,
- adhesive wear,
- fatigue wear, and
- macroshear wear

As shown in Table 2-2, there are several possible mechanisms for each type of wear.

2.3.4.1.1 Thermal Wear

Thermal wear encompasses a group of physical and chemical reactions in the course of which interatomic bonds are broken by thermal energy. These reactions include pyrolysis (thermal decomposition),

Table 2-2 - Wear Mechanisms in Friction Materials

THERMAL WEAR	ADHESIVE WEAR
PYROLYSIS	ORGANIC MATERIAL ADHESION
OXIDATION	BINDER
THERMOPARTICULATION	FRICTION DUST
MELTING	RUBBER
EVAPORATION	INORGANIC MATERIAL ADHESION
SUBLIMATION	METAL PARTICLES
EXPLOSION	ICE
ABRASIVE WEAR	FATIGUE WEAR
TWO-BODY	THERMAL
ASPERITIES	CYCLING
SCORING	SHOCK
CRACK EDGES	MECHANICAL
PIT EDGES	REPEATED BRAKING
THREE-BODY	DRUMS OUT OF ROUND
WEAR DEBRIS	DISCS OUT OF PARALLEL
ROAD DUST	
	MACRO-SHEAR WEAR
	ACROSS THE PAD
	AT CORNERS AND EDGES
	THROUGH HEAT-AFFECTED LAYERS

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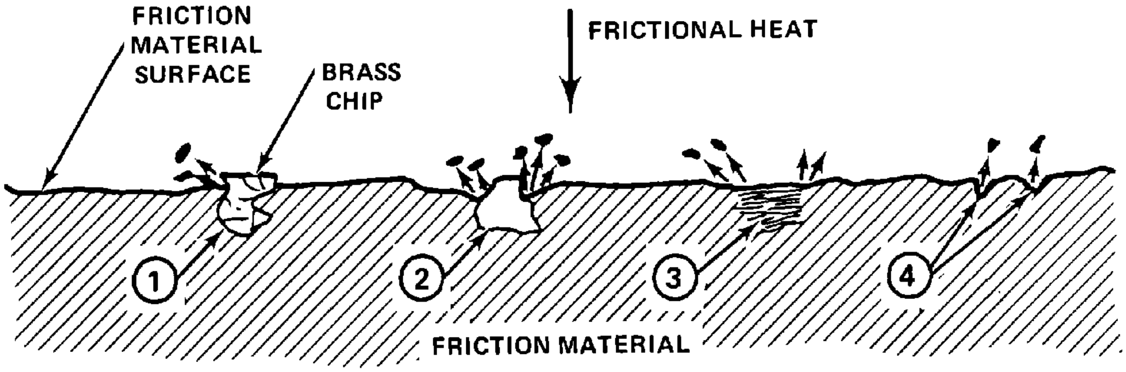
oxidation, thermoparticulation, explosion, melting, evaporation, and sublimation. Their rates increase exponentially with temperature, and in extreme cases they result in fade.

Pyrolysis probably occurs predominantly at the centers of linings and pads and to a lesser extent at the corners and edges. Oxidation, on the other hand, probably predominates at the corners and edges and is less severe at the center. Explosive reactions occur under highly abusive braking conditions, where the rate of heat input is so high that solids are converted to gases well beneath the surface; because these gases are greater in volume than the solids they displace, they create a pressure that ruptures the lining in an explosive manner. Four such reactions are represented in Figure 2-10.

It might be thought that rapid thermal wear occurs only at high soak temperatures.* In fact, however, thermal wear probably

*Soak temperatures are temperatures measured during dynamometer or vehicle testing, using a thermocouple located in the friction material or in the rotor, generally at a distance of 20 to 50 mils from the sliding interface.



1. $CaCO_3$ (s) → CaO (s) + CO_2 (g) *
2. CASHEW DUST (s) → CO_2 (g) + H_2O (g) + C (s)
3. ASBESTOS → H_2O (g) + OLIVINE (s) + ASBESTOS FIBRILS (s)
4. PHENOLIC RESIN → CO_2 (g) + H_2O (g) + C (s)

(S): SOLID
(G): GAS

*THE BRASS CHIP CONDUCTS HEAT RAPIDLY INTO THE FRICTION-MATERIAL SURFACE.

Figure 2-10 - Mechanism of Explosive Thermal Wear

occurs at appreciable rates at low soak temperatures as well. It has been shown that the materials in a sliding friction couple contact each other at the tops of asperities on their surfaces. There is considerable evidence to indicate that the temperature increase at these asperities for low sliding speeds is represented by the equation(2-16, 2-17)

$$T - T_o = (g\mu vw/4aJ)[1/(k_1 + k_2)]$$

where

T is the "flash" temperature

T_o is the soak temperature

g is the acceleration due to gravity

μ is the coefficient of friction

v is the sliding velocity

w is the load on the asperity

a is the radius of the asperity junction

J is the mechanical equivalent of heat

k_1 is the thermal conductivity of the disc

k_2 is the thermal conductivity of the slider

Modifications of this equation have also been developed for high sliding speeds. Experiments indicate that the flash temperature may be as high as 1400°F (760°C) if the soak temperature is 650°F (343°C). This flash temperature is high enough to cause rapid localized pyrolysis of the organic compounds used in friction materials, as well as conversion of fibrous asbestos to powdery olivine and transformation of pearlite to martensite in the cast-iron mating surface.

2.3.4.1.2 Abrasive Wear

Abrasive wear is of two types: two-body wear (Figure 2-11) and three-body wear (Figure 2-12). Plowing by asperities on the rotor surface and plowing by edges in rough-machined, scored, cracked, or corroded (pitted) rotors are examples of two-body wear. Grinding by wear debris and by foreign particles such as sand, clay, mud, or salt in the sliding interface is three-body wear.

Abrasive wear would be expected to increase with temperature. It increases also with the braking load and with the concentration, size, and hardness of foreign particles. It may be accompanied by negative fade.

Figure 2-13 is a Bendix scanning electron photomicrograph of a dynamometer-tested friction material showing the abrasive wear tracks on the surface. Several adherent wear debris particles are similar in size to the wear track widths.

2.3.4.1.3 Adhesive Wear

Adhesive wear, illustrated in Figure 2-14, involves the adhesion of organic and/or inorganic materials to the rotor and the subsequent tearing or separation of these materials from the lining or pad.

Organic constituents of friction materials include the binder, friction modifiers and elastomeric compounds. Inorganic constituents include zinc powder, brass chips, and asbestos. Little is known about the tendency of these materials to adhere to the cast iron used in today's drums and discs, though experience with hot elastomeric compounds suggests that elastomers are very likely to stick. Experiments at Bendix Research Laboratories indicate that brass chips will alloy with certain nonferrous rotor alloys.[2-18] When this occurs, metal is transferred from the rotor to the lining, scoring the surface of the rotor and in turn subjecting the lining to a high rate of two-body abrasive wear.

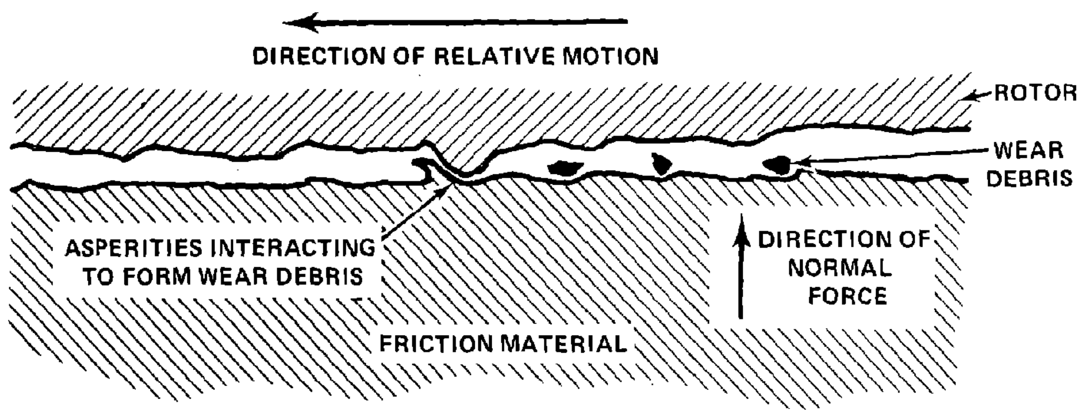


Figure 2-11 - Mechanism of Two-Body Abrasive Wear

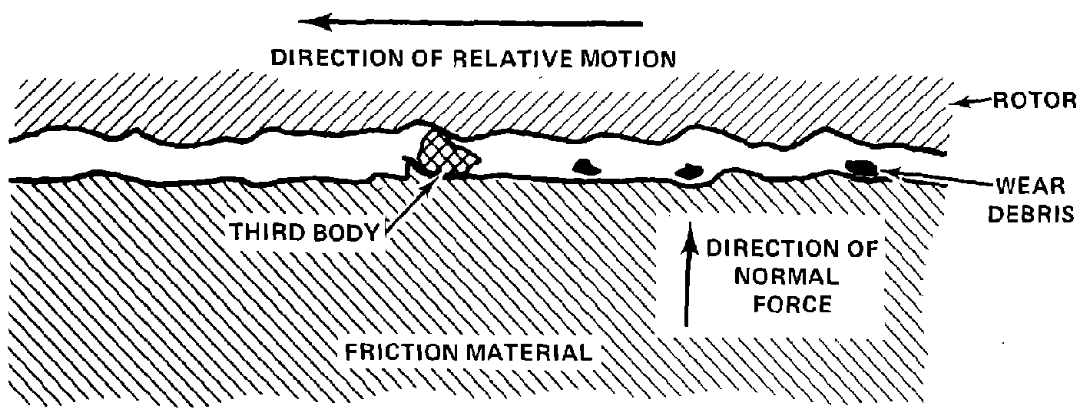


Figure 2-12 - Mechanism of Three-Body Abrasive Wear

Figure 2-13 - Scanning Electron Photomicrograph Showing Abrasive Wear Tracks on Friction Material Surface and Adherent Wear Debris Particles

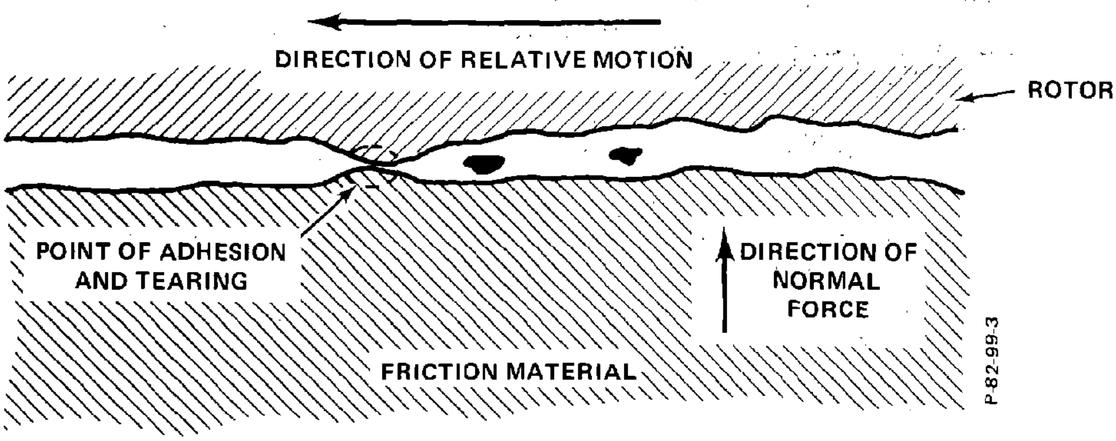


Figure 2-14 - Mechanism of Adhesive Wear

Adhesive wear probably increases with temperature, braking load, and the concentration of adherent components in the friction material. It is also caused by the presence in the friction material of metal particles capable of solution in or reaction with the rotor alloy, increasing with the size and concentration of such particles. Because this type of wear can cause stick-slip, it may be associated with brake noise.

2.3.4.1.4 Fatigue Wear

Fatigue wear (Figure 2-15) is most commonly observed in metal bearings. However, it may also be experienced by organic friction materials, occurring in two forms, thermal and mechanical.

Thermal fatigue is caused by repeated heating and cooling. Such repeated temperature changes impose cyclic stresses on the surface material, which heats and cools more rapidly than the bulk material and thus expands and contracts to a greater extent. Because of their low thermal conductivities, the thermal gradients and resultant thermal stresses in organic friction materials may be higher than those in metals.

Thermal-shock cracking may be thought of as a special case of thermal fatigue, occurring as a result of a single abusive loading.

Mechanical fatigue is caused by repeated mechanical stressing. Because of the frequency of brake use, friction materials are subjected repeatedly to both compression and shear forces. Additional stresses are also applied repeatedly if drums are out-of-round, if discs are out-of-parallel, or if rotor thickness is not uniform.

Figure 2-13 shows the initiation of fatigue wear around the large cashew particle. This material swells when heated and thus the surface wears. After cooling, the particle contracts, cracks, and pulls away from the edges. When the particle is completely loose, it can fall out.

2.3.4.1.5 Macroshear Wear

Three types of material removal fall in the category of macroshear wear, which is illustrated in Figure 2-16.

A fracture, in shear, may occur across the entire brake pad under extremely heavy loading, especially if the friction material has previously been weakened by heat. This is a sudden rather than a gradual type of wear.

Fracture at the edges and corners of a piece of friction material is another type of macroshear wear. Oxidation of organic components weakens the friction material at these locations.

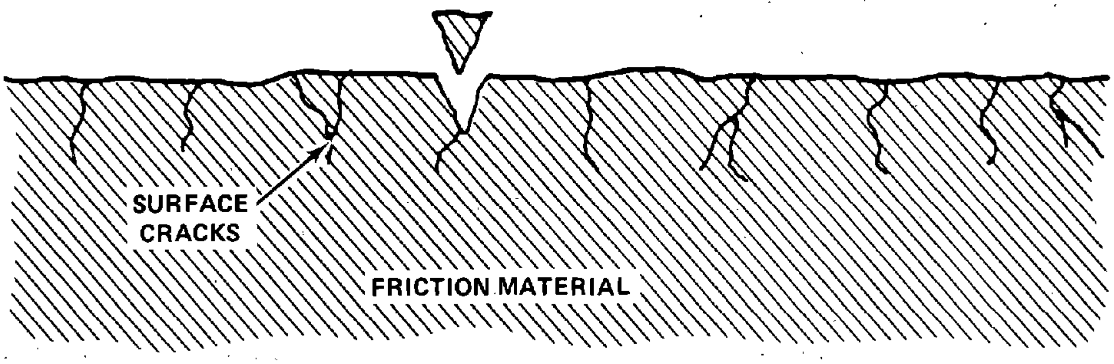


Figure 2-15 - Mechanism of Fatigue Wear

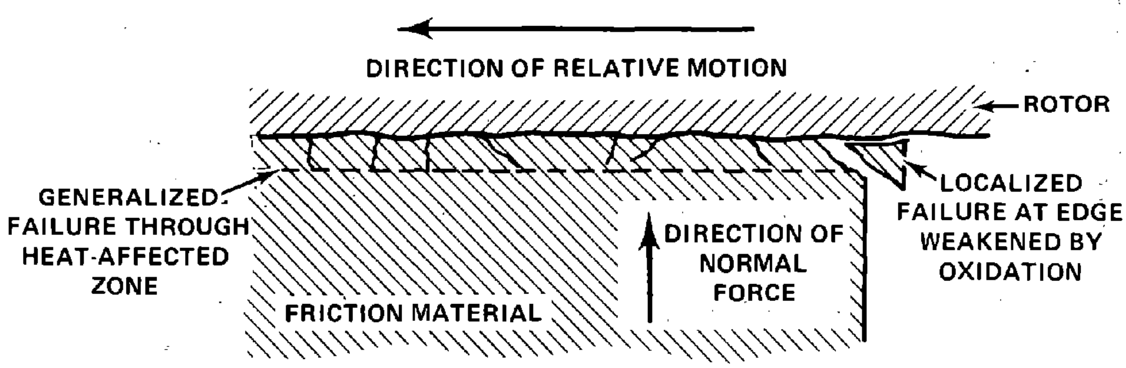


Figure 2-16 - Mechanism of Macroshear Wear

Fracture at the edges and corners of a piece of friction material is another type of macroshear wear. Oxidation of organic components weakens the friction material at these locations.

A third type of macroshear wear can occur when a friction material such as that shown in Figure 2-15 is subjected to heavy loading following thermal abuse. The heat-affected layer in the material pictured is about 100 mils deep, and from this layer organic material has been removed by pyrolysis. If sufficiently weakened, such a layer can be sheared away by a single, heavy brake application.

Whatever the mechanism, macroshear wear is promoted by nonuniform loading and by oxidation and thermal degradation of the binder. It is most likely to occur at elevated temperatures and under severe braking conditions. Its end products are typically large fragments of friction material that leave the surface rough. These fragments subject the remaining friction material to plowing or abrasive wear, and while they are present in the interface, friction behaviour will be erratic.

2.3.4.2 Predominant Wear Mechanisms

The predominant wear or emissions-generation mechanisms may be summarized simply (Figure 2-17):(2-19)

- Below 450°F:
  Abrasive and adhesive wear.
- Above 450°F:
  Thermal wear.

Figure 2-18 illustrates the wear loss of three different kinds of friction materials as a function of temperature, illustrating these predominant wear mechanisms.

2.3.4.3 Wear Equation

Recent work at Bendix Research Laboratories has indicated that each friction material wears according to a universal wear equation.(2-20)

$$\Delta W = k \cdot P^{a} \cdot V^{b} \cdot t^{c}$$

or

$$\log (\Delta W) = \log k + a \log P + b \log V + c \log t$$

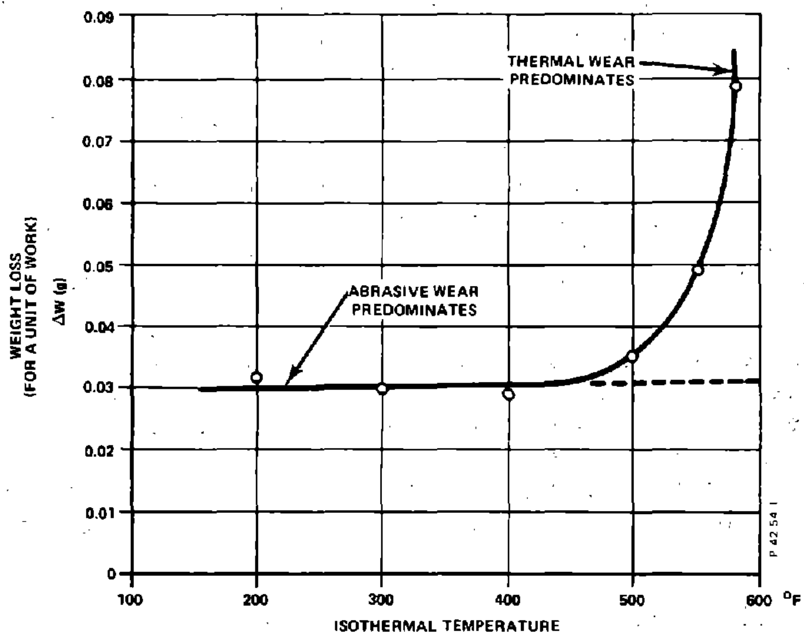


Figure 2-17 - Predominant Wear Mechanisms of Friction Materials

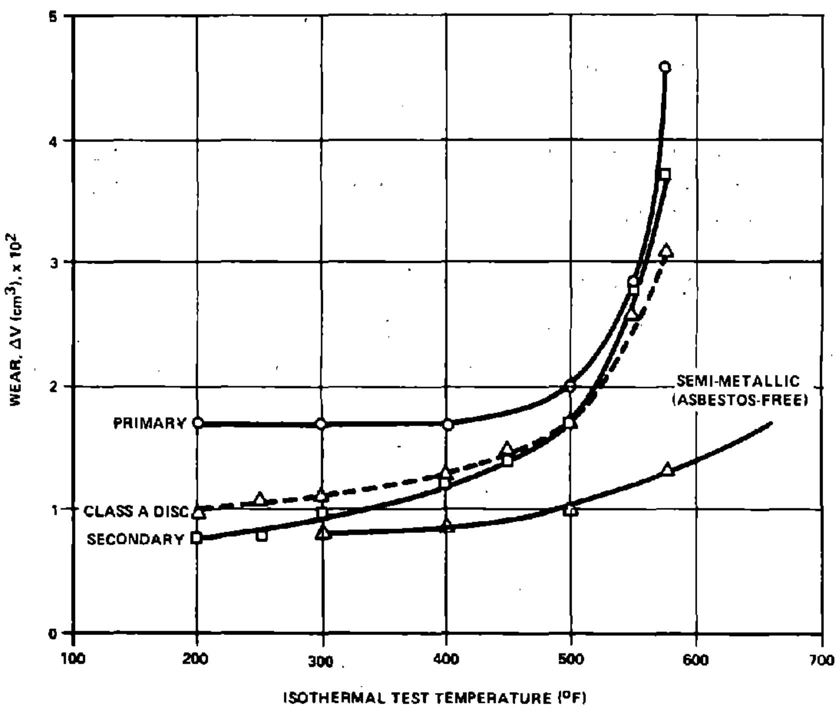


Figure 2-18 - Variation of Friction Material Wear with Temperature where

ΔW is the weight lost

k is the wear factor

p is the load

V is the sliding velocity

t is the time of sliding, and

a,b,c are constants characteristic of a given friction couple.

When further developed, this equation will be useful for predicting wear (and emissions) under various driving conditions.

2.3.5 Emissions of Particulate and Gaseous Emissions

2.3.5.1 Drum Brakes

Gaseous decomposition products in drum brakes are emitted from two areas:

- The space between the rotating drum and the stationary backing plate.
- The small holes in the backing plate itself (e.g., clearance holes, brake adjusting slot, etc.)

Particulates are emitted from the same two areas, although only small particulates would come through the holes in the backing plate. In drum brakes, some particles are not emitted but remain in the rotating drum. It is expected that some of these particles would eventually be emitted through the space between the rotating drum and stationary backing plate. Also, some large particles would be "ground up" and emitted as a number of smaller particles if they are trapped between the friction material and drum on subsequent braking or if they are trapped between the rotating drum and stationary backing plate. If the brake shoes are of riveted construction, then some particles can be trapped in the rivet holes and thus retained in the brake.

If convective cooling of drum brakes is improved in the future, as is desirable for safer operation and longer driving life, it is likely that fewer particles will remain trapped. The particles emitted, however, will probably be larger, as they will be subjected to grinding action for shorter periods of time.

2.3.5.2 Disc Brakes

As the disc brake is essentially an open braking system, it is expected that all particulate and gaseous decomposition products will be emitted. However, a small amount of particulates collect in the rivet holes of riveted disc brake pads and on some areas of the caliper.

2.3.5.3 Clutches

In the dry clutches commonly in use on "stick-shift" cars, there are very few openings for gases and particles to escape. The two main areas are:

- The area around the clutch fork, which generally has a rubber boot on it for protection of the clutch from road spray, sand, etc.
- A small opening at the lower front of the clutch to drain any oil, water, etc., which may get into the clutch.

Because of the construction, many particulates remain in the clutch housing.

2.3.6 Distribution and Changes in Brake and Clutch Emissions

Entrapped gases and pyrolysis gases released during braking or clutch slipping will be hot enough to mix rapidly with the surrounding air and become part of the air wake of the car. The higher molecular weight vapors will condense and eventually settle to the ground. The low molecular weight gases will disperse as part of the local atmosphere. Some of the condensible vapors may, of course, settle on small, air-borne dust particles and could be carried into the respiratory system as part of the breathing air.

The particle emissions will disperse in different ways depending on their size, shape, and density. Submicrometer-size particles, regardless of shape, will ordinarily remain air-borne until they are scrubbed out by rainfall or some other separating action. In effect they become a long-time part of the atmosphere.

Spherical particles in the 1.0 μm to 10 μm diameter range will settle, under gravity and in still air, at velocities from 12 to 1000 cm/hr, according to Stokes' law. Irregularly shaped particles of similar size and in turbulent air will settle at much slower velocities and could remain air-borne for hours or days. These particles cause the greatest aggravation in the human respiratory system because they collect in the tracheo-bronchial regions and, to some extent, in the alveoli.

Particles from 20 μm to 100 μm in diameter will settle as part of the dust trail left by the car or will collect with any larger particles in mechanical traps in the car. Eventually these larger-size particles will fall or be shaken out of the car and become part of the road dust.

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SECTION 3

MATERIALS SELECTIONS

3.1 BACKGROUND

Friction materials and rotor materials vary in composition according to their source. There are original equipment manufacturers (OEM) and aftermarket (AM) friction materials in addition to foreign friction materials; there are wide variations according to use and origin. Friction materials are the expendable item of the friction pair. Consequently, friction materials are usually replaced two to five times during a vehicle's life-time, while rotor materials are seldom replaced. However, rotor materials are occasionally turned, that is, the rubbing surface is machined so that fresh metal is exposed as a new rubbing surface.

The asbestos content of any particular friction material is not known, as this is information proprietary to the manufacturer. With the use of modern analytical tools, it is possible to estimate the asbestos content to the nearest $\pm$ 2 weight percent. Thermogravimetric analysis yields the organic/inorganic ratio as well as the inorganic residue remaining above 800°C. X-ray diffraction indicates the inorganics, other than asbestos, and their relative amounts.

3.2 MATERIALS SELECTIONS FOR PROGRAM

3.2.1 Friction Material Selections

A completely balanced program would contain friction materials comparable to most of those in normal customer usage. If a large number of tests can be run, it is easy to fulfill that requirement. If only a small number of tests can be run, the selections are less representative and much more critical. The objective of the program was to obtain brake emissions from disc and drum friction materials, OEM and AM friction materials, friction materials from several different manufacturers, both new and used friction materials, and repeats of at least one axle set of friction materials. This was a considerable task since only a limited number of tests were funded. Three vehicle tests were planned in such a way as to accomplish these goals. It is believed that the friction materials used are representative of a high proportion of those on the road today.

A custom-size vehicle was chosen as a median between the compacts and luxury-size vehicles prevalent in the country. The vehicle was equipped with the front disc pads and the rear drum primary and secondary lining combinations, listed in Table 3-1. Each of the front axle and rear axle friction materials was produced by different manu-

Table 3-1 - Vehicle Configurations and Lining Selections

Test Number	Description	Lining Selections	Manufacturers	Remarks
1	Original Equipment	Front Disc: TP-1003 Drum Rear: Primary: 4641 Secondary: H3133	Panelyte Division Thiokol Corporation Friction Materials Division Bendix Corporation	• Class A type organic disc pads.
2	Aftermarket Equipment	Front Disc: R-4528-4-FF Drum Rear: Used OEM Combination from Test 1.	Raysbestos-Manhattan Corp. Friction Materials Division Bendix Corporation	• No metallic chips in any linings • Discs were not turned • Drums were not turned
3	Aftermarket Equipment	Front Disc: WB-60-FF Drum Rear: Primary: ABB-249-FF-PRI Secondary: ABB-250-FF-SEC	Worldbestos Division Firestone Tire & Rubber Co. ABEX Division American Brakeblock Corp.	• Disc pads and secondaries contained brass chips. • Disc were turned. • Drums were turned.

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facturers. The vehicle was received new with less than 5 miles on the odometer. Prior to vehicle test 1, all rotors were adjusted to their OEM condition and unused disc pads and linings were installed to replace those with partial use. Vehicle test 1 was made with the OEM test configuration.

Vehicle test 2 was a simulation of a typical consumer practice: the replacement of the front axle friction materials only (Table 3-2). The discs and drums were not turned. The rear lining combination was considered "a repeat." The rear lining combination was also considered as an extended test of "used" friction materials to ascertain the nature of the brake emissions with extended use against their original rotor. The front disc pads were purchased as aftermarket friction materials sold in the Detroit area. The manufacturer was among the larger AM manufacturers.

Table 3-2 - Surface Roughness Measurements on Turned Discs and Drums for Vehicle Test 3

	Front Brakes		Rear Brakes	
	Right (Shrouded)	Left (Normal)	Right (Shrouded)	Left (Normal)
Specification	15-80 microinches		60-120 microinches	
As Machined	28-30	27-32	90-95	75-85

Vehicle test 3 was a simulation of a second consumer practice: the replacement of friction materials on both axles in addition to turned discs and drums (Table 3-1). The final conditions of the rotors and drums are listed in Table 3-2. The front and rear axle friction materials were produced by manufacturers different from those for the friction materials used in any other vehicle tests, and both manufacturers were among the larger AM manufacturers.

Briefly summarizing the three vehicle tests, five different friction material manufacturers are represented. Both OEM and AM disc pads and drum linings were selected. The OEM manufacturers represented supply a large part of the OEM market and the AM manufacturers represented supply a large part of the aftermarket. All AM friction materials were purchased over-the-counter at various locations in the Detroit area.

3.2.2 Contents of the Friction Materials

The asbestos content of the friction materials used was determined by the analytical methods mentioned earlier. The percent of asbestos estimated for each material is listed in Table 3-3. This information was obtained in order to ascertain, in later stages of the program, whether there is any correlation between the asbestos content of a friction material and the asbestos content of its wear debris.

Table 3-3 - Estimated Asbestos Content

Test Number	Description	Lining Identifications		Estimated Wt %			
				Total Residue*	Olivine	Other**	Asbestos
No. 1	ORIGINAL EQUIPMENT	Front Disc:	TP-1003				
			Inner	60	55	5	64
			Outer	61	56	5	65
		Drum Rear:					
		Primary:	4641 (EBEF)	68	63	2	76
		Secondary:	H3133 (DUGF)	59	55	4	64
		Clutch:	US 969 (Used in all tests)	66	30	36	35
No. 2	AFTERMARKET	Front Disc:	RM R4528-FF	63	60	3	70
		Rear Drum:	Used OEM Combination 4641 H3133				
No. 3	AFTERMARKET	Front Disc:	WB 60-FF	71	52	19	60
		Rear Drum:					
		Primary:	ABB-249-FF-PRI	63	63	-	74
		Secondary:	ABB-250-FF-SEC	66	62	4	73

*By thermogravimetric analysis at 900°C.

**Estimated from x-ray diffraction.

SECTION 4

VEHICLE AND INSTRUMENTATION

4.1 VEHICLE DESCRIPTION

In this program, a passenger car of medium weight (4850 lbs test weight), produced in high volume was selected. It was equipped with a three-speed manual transmission, ventilated cast-iron disc brakes on the front, and cast-iron drum brakes on the rear. This vehicle was selected in order that the emissions from clutches and from disc and drum brakes could be tested simultaneously on a vehicle size representing a large percentage of the present vehicle population. A detailed vehicle description is given in Table 4-1.

Table 4-1 - Test Vehicle Description

General Description		
1971 two-door hardtop		
V-8 engine		
Three-speed standard-shift transmission		
Power brakes (disc front/drum rear)		
Power steering		
Air conditioning		
Vehicle Weight		
Curb weight:	Approximately 4000 lbs	
Test weight:	4850 lbs (with driver and passenger)	
Tires		
H 78-15		
Brakes		
Front Disc:	Inner Pad Area:	8.5 in^2
	Outer Pad Area:	11.2 in^2
Rear Drum:	11 inch diameter by 2-1/2 inch	
	Primary Lining Area:	21.0 in^2
	Secondary Lining Area:	27.3 in^2

4.2 BRAKE TEST INSTRUMENTATION

The vehicle was instrumented with standard brake test instrumentation (Figure 4-1):

Brake pedal application counter

Front and rear brake hydraulic pressure gages

U-tube decelerometer

Brake lining temperature pyrometers for each wheel (thermocouples were placed in one lining of each wheel in accordance with the SAE specification J-843

Twelve-position thermocouple switch and pyrometer to monitor gas trap and particle trap collector temperatures

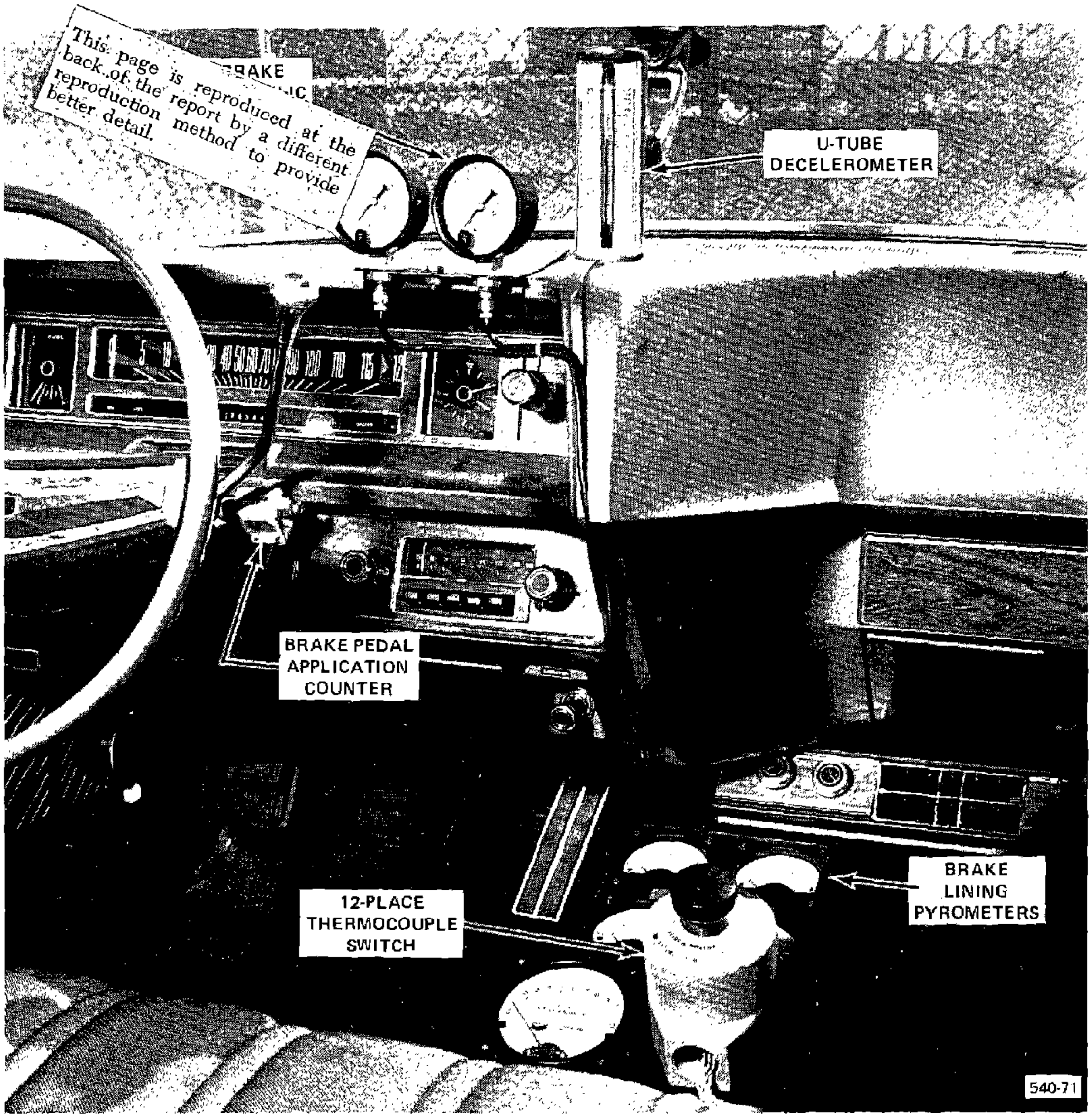

Figure 4-1 - Vehicle Instrumentation for Friction Material Testing

SECTION 5

EMISSIONS COLLECTION SYSTEMS

5.1 OPERATION REQUIREMENTS

5.1.1 Operation and Design Criteria

Only 100 percent collection can assure a reliable measure of the total emissions from the clutch, drum and disc brakes. The composite nature of the emissions, including gases, volatile liquids, and solid particles, makes it impossible to obtain a representative sample on anything less than a 100 percent collection. The first requirement for the emissions collector, then, was that it collect all the particle and vapor emissions from the clutch and brakes. It also had to store these emissions during a complete test cycle without changing them.

Another important requirement for the emissions collector was that it should prevent intrusion of contaminants, or at least of contaminants that could not be positively distinguished from brake emissions. Oxygen and nitrogen had to be excluded from this restriction since operating in an inert gas atmosphere would seriously change the character of the emissions.

The collection system should not, of course, significantly change the ordinary operating conditions of the clutch or brakes. This means it should not materially change the heat flow and that the air flow rate through clutch and brake chambers had to be similar to that under ordinary operating conditions. The flow pattern did not need to be identical since this would not affect the generation of emissions at low temperatures, but only the way in which they were carried out of the brake and clutch chambers.

The front disc collector had to be capable of operating at brake temperatures to 650°F (340°C) with the sealing surface operating up to 400°F (205°C). The rear drum collector had to be capable of operating at brake temperatures to 500°F (260°C), the sealing surface operating to approximately 350°F (177°C). The clutch collector had to be capable of operating at temperatures to 250°F (121°C).

Finally, the collection system had to permit easy separation and analysis of the different types of emission - large and small particles down to 0.2 μm size, condensable vapors, and volatile gases. If expensive preliminary separations had to be carried out in the laboratory, an already difficult and time-consuming analysis would become even more extended and costly.

The major requirements for the emissions sample collection system may be summed up, therefore, as follows:

- Collect all particulate and gaseous emissions,
- Store collected emissions unchanged,
- Prevent intrusion of contaminants,
- Maintain ordinary braking and clutching conditions,
- Be operable at high temperatures, and
- Permit easy separation and analysis of emissions.

5.1.2 Emission Expected

Appendix A shows a series of wear debris calculations which included the chemical composition and the amounts of wear debris expected. This information was necessary to insure proper sizing of the emission collection hardware.

5.2 OVERALL DESIGN CONCEPT

5.2.1 Air Flow of a Typical Collection System

The basic design concept of each brake emissions collection system is shown in Figure 5-1. Air from inside the vehicle was pulled into a bed containing Drierite and calcium oxide pellets which remove water and carbon dioxide from the air. After passing through the bed, the air passed through a filter to remove all particles larger than 0.2 μm (8×10^{-6} inches). The filtered air was then routed to the sealed brake or clutch assembly through clean Teflon tubing. The air stream, along with wear particles and gases, then passed out of the brake or clutch through Teflon tubing surrounded by heating coils to keep the gases at 200°F (93°C) in order to avoid condensation. This stream passed through two filters to remove the airborne particles and preserve them for analysis. The stream then passed through three cold traps in order to condense and trap the gases evolved during braking and preserve them for analysis. Finally, the air stream passed through a flowmeter, the vacuum manifold, and an air pump run by the vehicle engine, finally being expelled to the atmosphere.

Figure 5-2 shows the engine-driven air-pump installation under the hood. The pump was run by a belt attached to an added pulley attached to the drive shaft of the alternator. Thus the air pump had two modes of operation:

- During engine idle, the pump ran at a low fixed speed.
- During vehicle operation, the pump ran at a speed proportional to the engine speed.

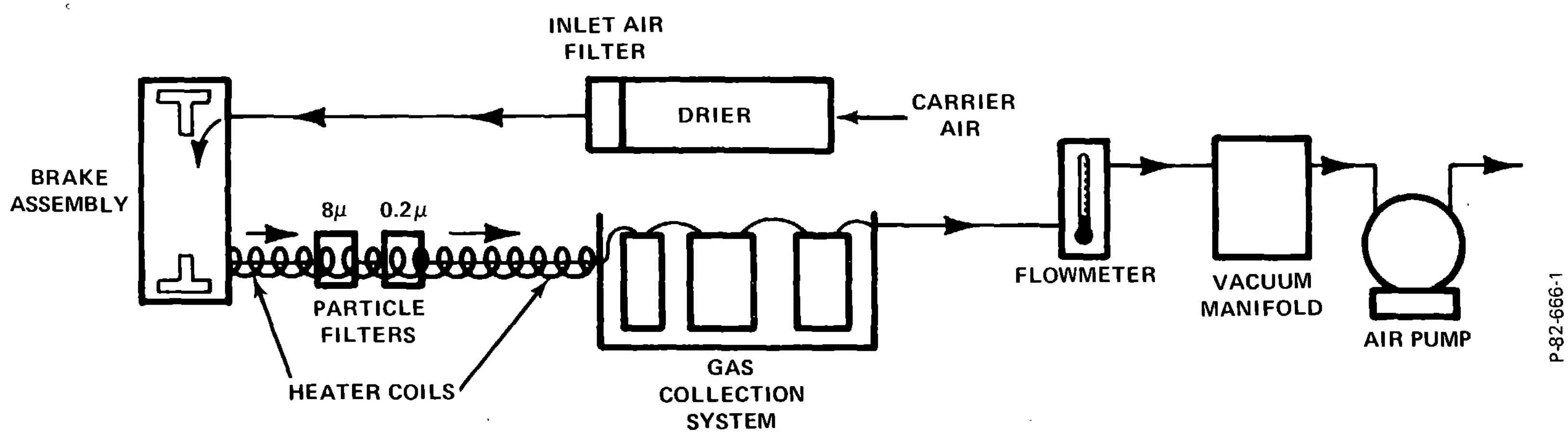

Figure 5-1 - Schematic Diagram for Air Flow of Typical Particulate and Gas Emission Collection System

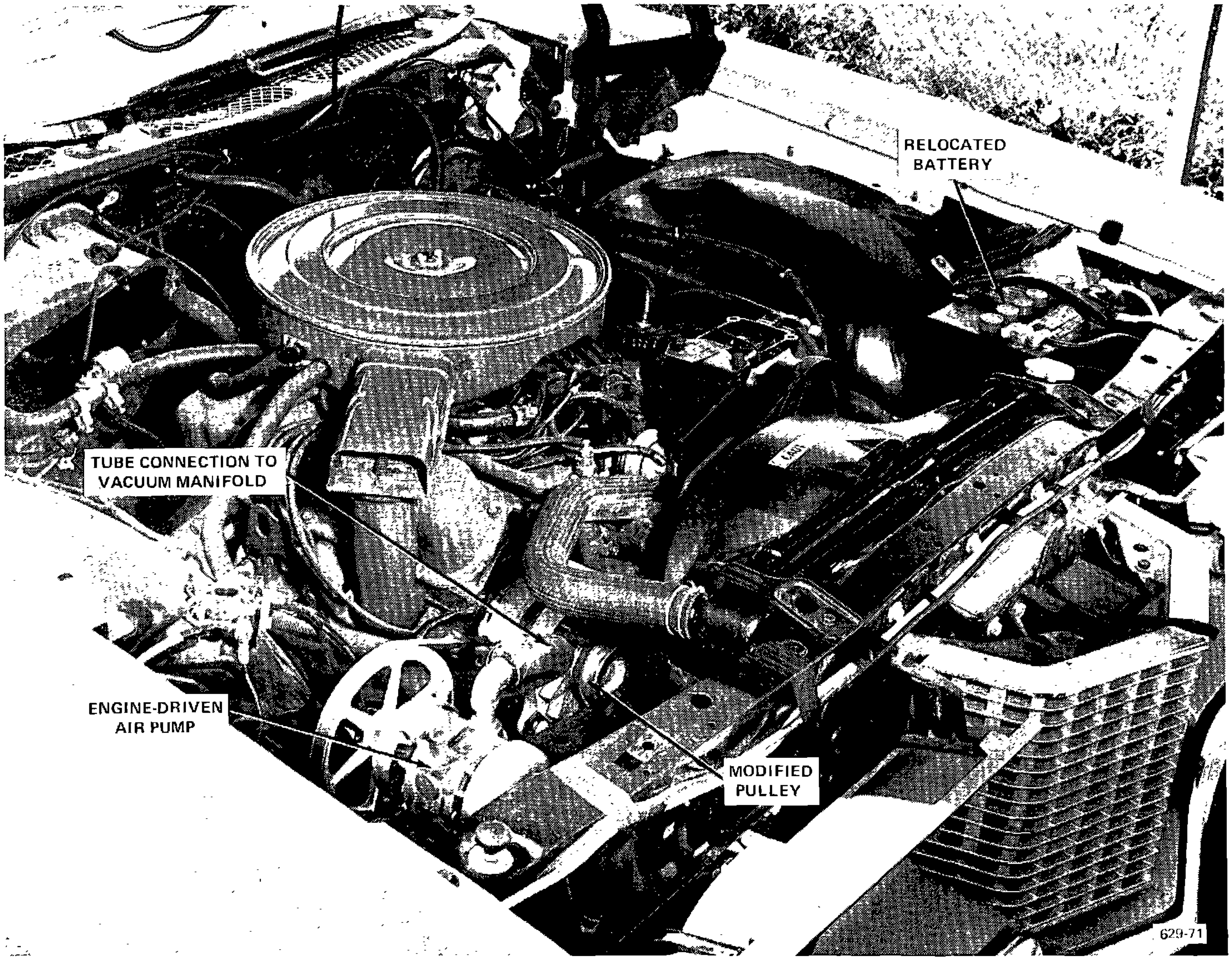

Figure 5-2 - Air Pump Installation in Engine Compartment

5.2.2 Collection Systems Used

Collection systems such as those described above were attched to the following: right front disc brake, right rear drum brake, and the clutch. The left front and left rear brakes were not modified in any way but were monitored to insure that the wear on the right side was not changed significantly by the collectors.

Figure 5-3 shows, mounted in the front seat of the test vehicle, the front-brake inlet air filter and gas collection system, the clutch gas collection system, and the twelve-position thermocouple switch and pyrometer used to monitor gas and filter trap temperatures. Figure 5-4 shows, as mounted in the rear seat of the test vehicle, the rear-brake air filter and gas collection system, the clutch air filter, and the electrical system.

5.2.3 Electrical System

The electrical system mounted in the rear seat consisted of two batteries, one inverter, and two variable transformers, and was used to supply AC voltage to the heating coils.

Figure 5-5 shows the schematic for the electrical system.

The inverter was capable of changing 12-volt DC power to 60-Hz, 120-volt power with an output of 400 watts continuously. Two extra batteries were installed to provide sufficient electrical capacity for 10 hours of testing. The inverter was separated by relays from the batteries in order that peak voltages occurring during vehicle start up did not damage the inverter. [illegible]is system consisted of power and latching relays and a pushbutton swit[illegible]er the vehicle was started, the pushbutton switch was used to en[illegible]he latching relay which in turn energized the power relay, prov[illegible] power to the inverter. When the vehicle was shut down for any [illegible] the power to the latching relay was removed and thus the power re[illegible]also de-energized. The AC output was regulated to the heater [illegible]se of two variable transformers thus allowing temperature adjustme[illegible] batteries were recharged each night in order to provide sufficie[illegible] for the following day.

5.3 PARTICULATE [illegible]

5.3.1 Fi[illegible]ers

Two [illegible] 47 mm filter holders joined in series were used for the collection of airborne particulates. These holders were sealed with O-rings, fabricated from stainless steel for protection against corrosion, and loaded with standard 47 mm diameter filters. Nuclepore filters were used. These filters were made from a smooth film of polycarbonate plastic with a number of circular pores through them. The pores did not restrict the flow of gases significantly as particle collection proceeded. The filter holders were heated by tape heaters wound

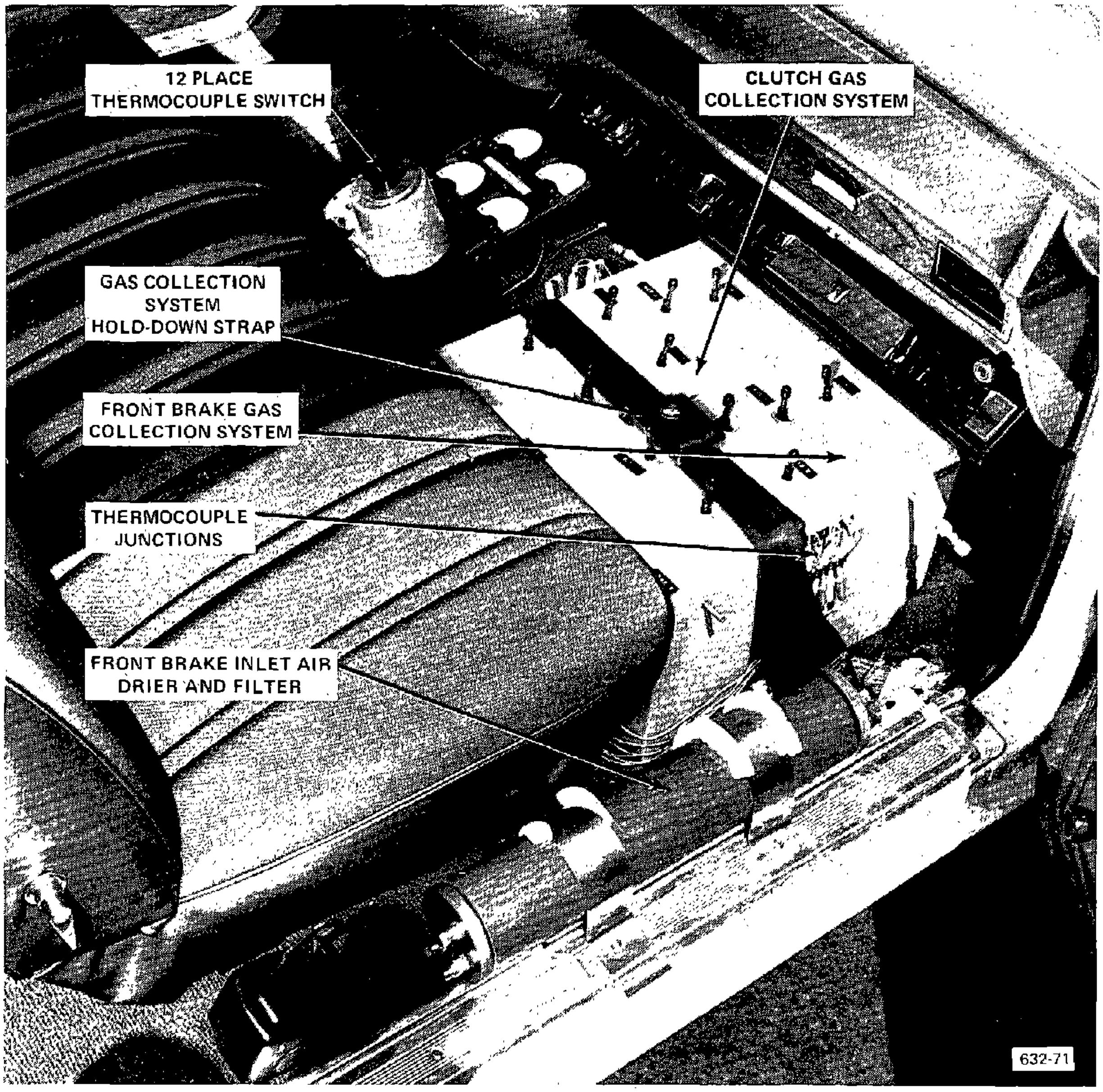

Figure 5-3 - Vehicle Instrumentation (Front Seat Area)

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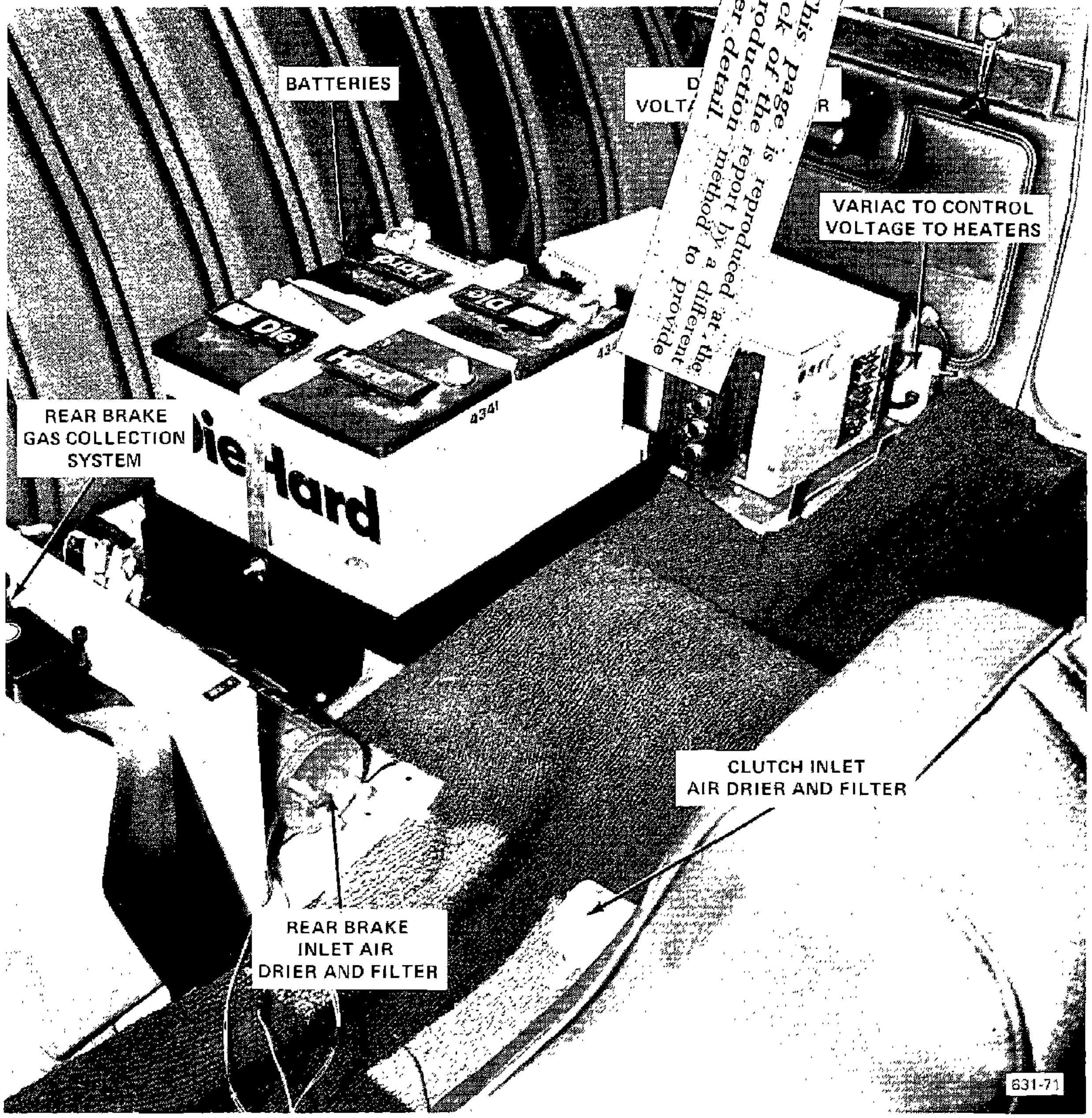


Figure 5-4 - Vehicle Instrumentation (Rear Seat Area)

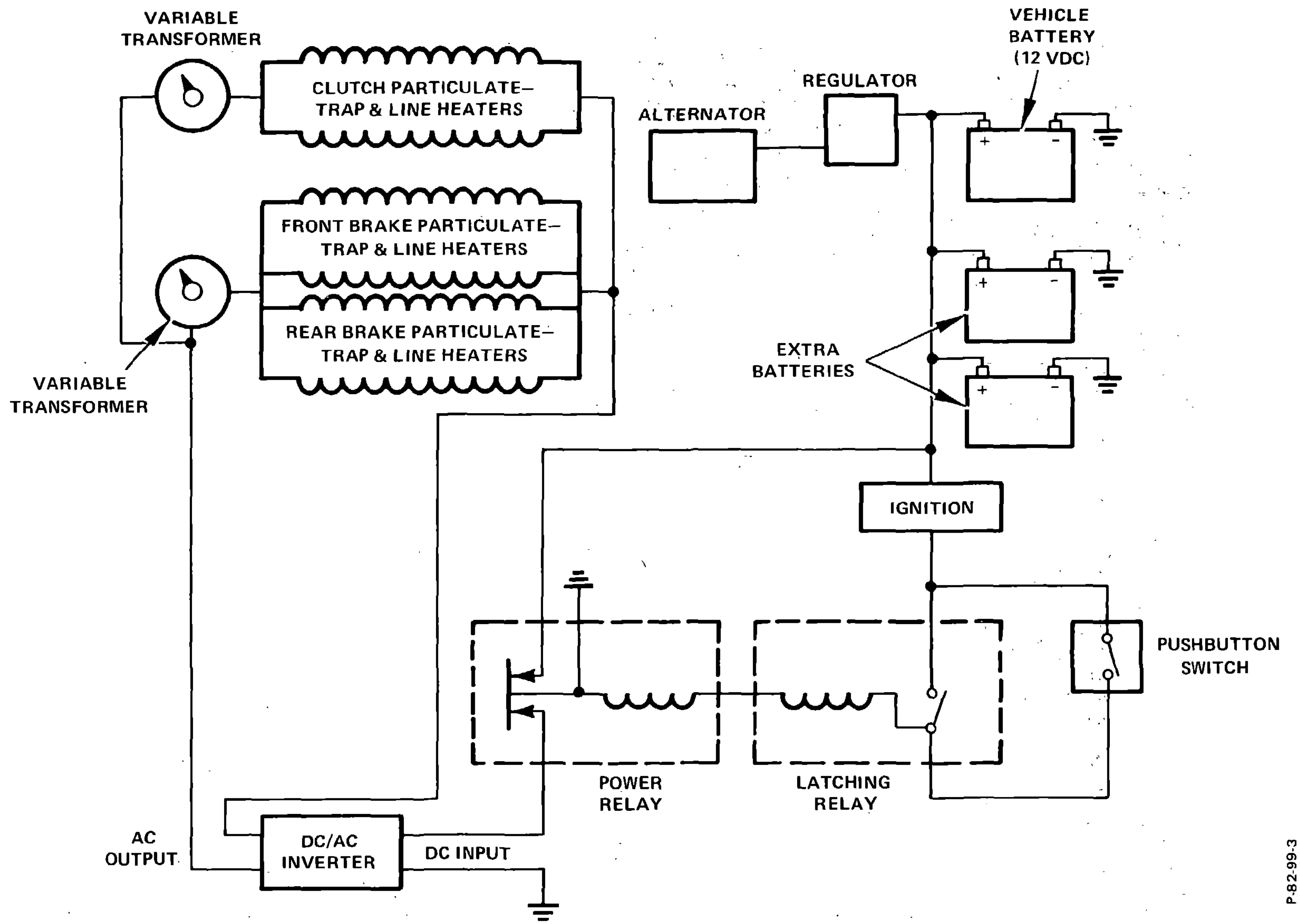


Figure 5-5 - Electrical Schematic for Particulate Trap and Transfer Line Heaters around the outside and controlled by a variable transformer within the test vehicle. The same configuration was used in all three collectors (front brake, rear brake, and clutch).

5.3.2 Filter Flow Characteristics

At the beginning of the program, no data were available for the flow characteristics for any type of filter when loaded with brake wear debris. Consequently a series of simple tests was performed; the results are included as Appendix B. The following results were noteworthy:

- The pressure drop change across an 8.0μ Nuclepore filter loaded with up to 1.0 gram of wear debris was not high enough to present problems in the program.
- Wear debris was easily removed from Nuclepore membranes such that no significant error was introduced when debris from several membranes was combined.

5.4 GAS COLLECTION SYSTEMS

5.4.1 Design and Fabrication of Traps

To withstand handling and road shocks, it was deemed necessary to design and build rugged gas traps for both condensable and noncondensable gases.

Figures 5-6 shows the schematic for the condensable-gas trap. The body of the trap and the tubing were made of stainless steel. The top was threaded so that it seated against an O-ring to provide a vacuum-tight seal.

Figure 5-7 shows the schematic for the noncondensable-gas traps. The trap was designed so that it could be filled with granular activated charcoal. The charcoal was held 3/8 inch above the bottom of the trap by a stainless steel screen. This allowed a small volume for the gases to permeate toward the outside walls before they were absorbed on the charcoal surfaces or passed through the charcoal bed to the exit port.

Figure 5-8 shows the schematic of the activated-charcoal trap top and the plug used to fill the trap once the top had been threaded on. An O-ring against a 45-degree bevel provided a vacuum seal.

Figure 5-9 shows the complete gas trap. Figure 5-10 shows an exploded view of the trap.

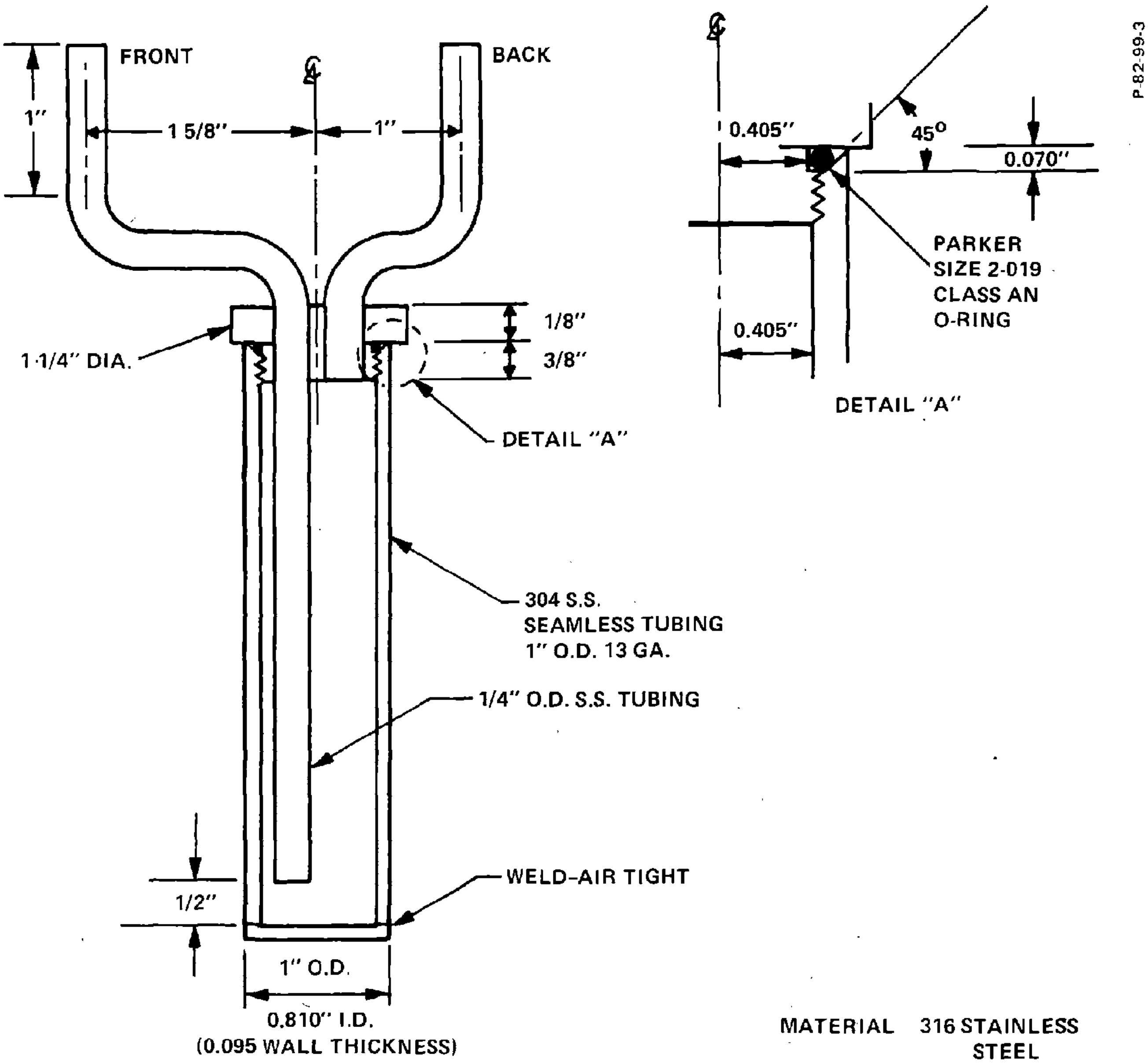


Figure 5-6 - Condensable-Gas Trap

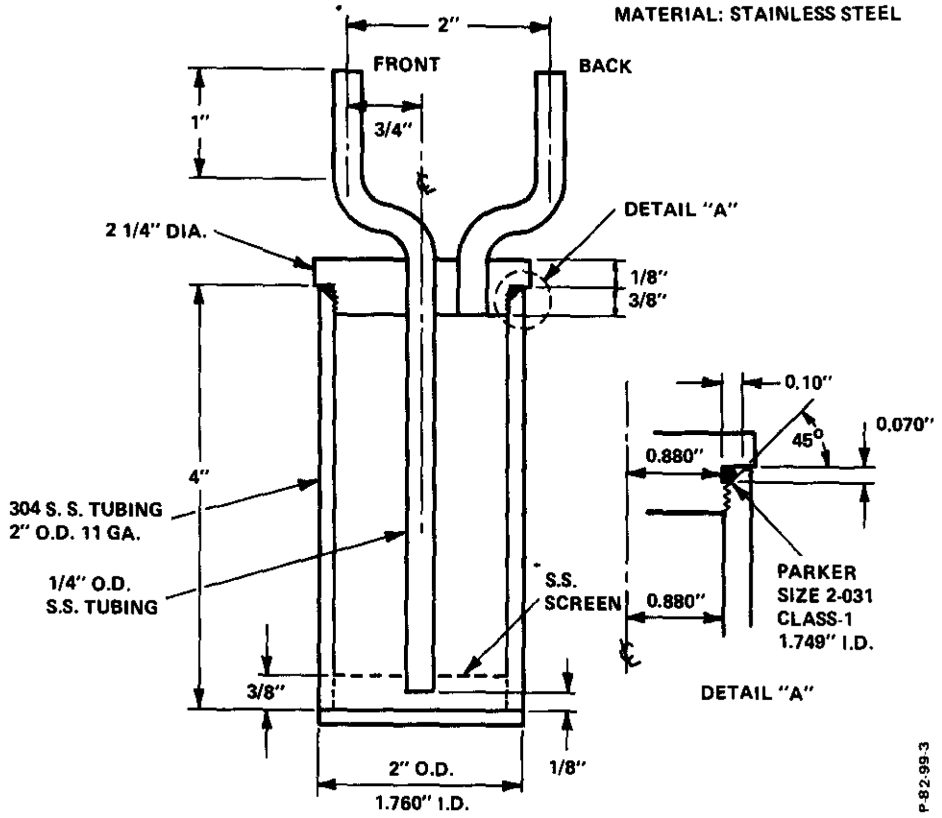


Figure 5-7 - Activated-Charcoal Gas Trap - Sectional View

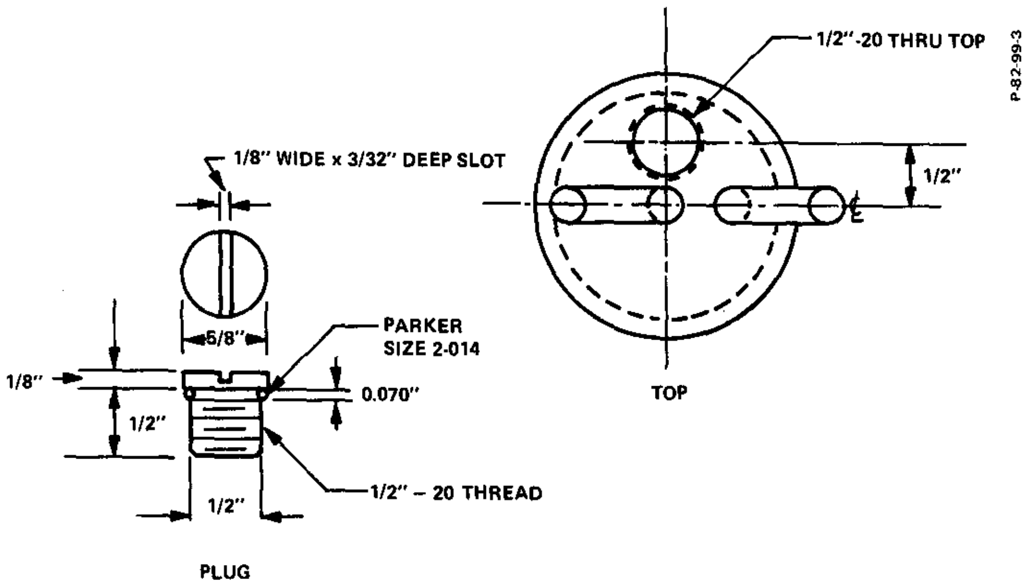


Figure 5-8 - Activated-Charcoal Gas Trap - Top View

Figure 5-9 - Activated Charcoal Gas-Trap

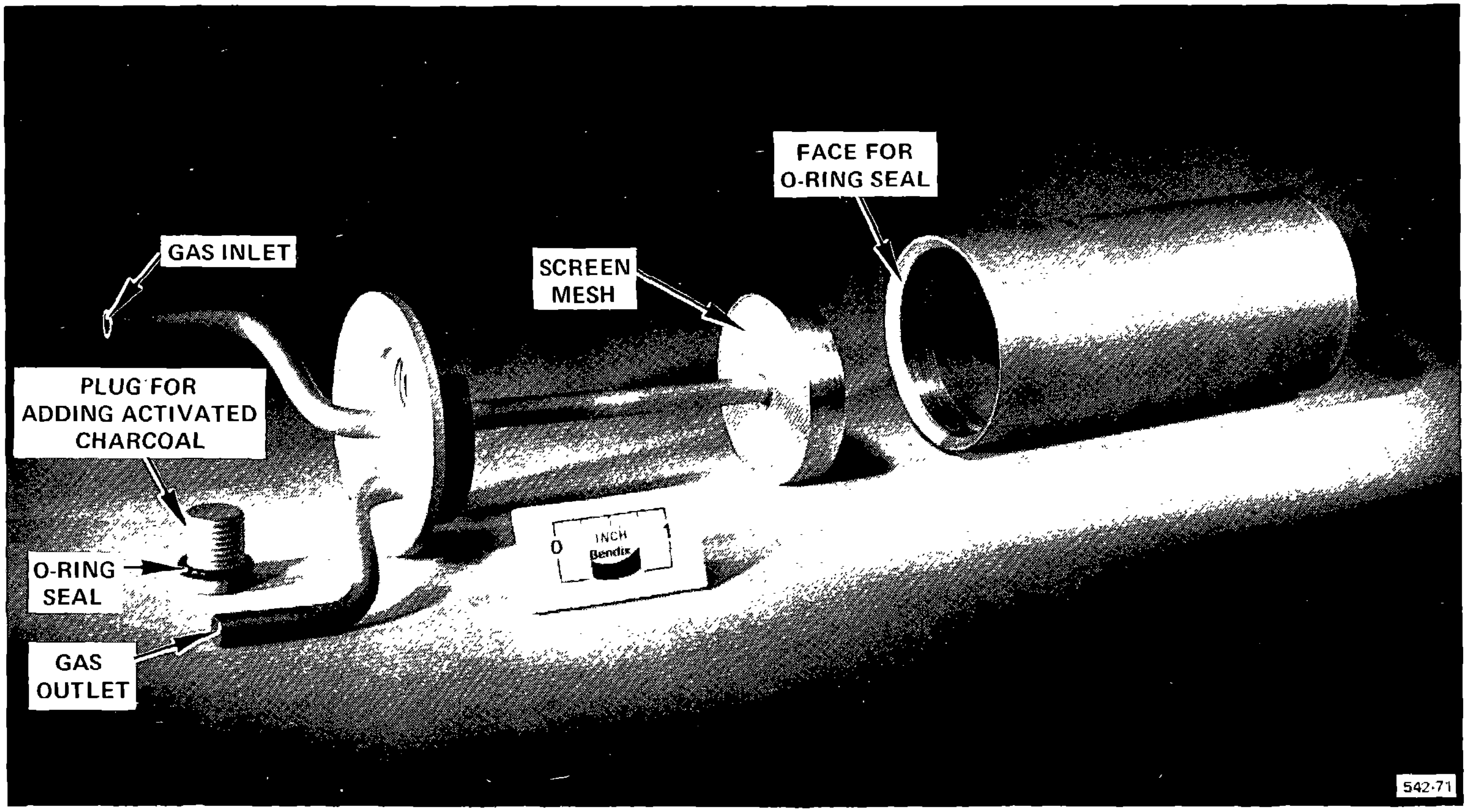


Figure 5-10 - Exploded View of Activated Charcoal Gas-Trap

5.4.2 Operation

The gas traps were connected in series such that the gases flowed through the condensable-gas trap first and then through two noncondensable-gas traps containing activated charcoal. Valves were installed at the inlet and exit of each trap. The traps were kept in a custom-made metal box lined with styrofoam, 1-1/2 inches thick, as shown in Figure 5-11.

The three gas traps were held at approximately -70°C (-95°F) with solid carbon dioxide. For the disc brake collector, which had higher gas flow rates, a 2-foot length of 1/4-inch OD tubing was added before the condensable gas trap. This was found necessary to prechill the gases, or otherwise no condensation would occur in the first trap.

5.5 DISC BRAKE COLLECTOR

5.5.1 Shroud Design and Construction

The brake emissions collector for the right front disc brake consisted of a sheet-metal duct, or shroud, completely covering the caliper and disc, and an emission storage unit consisting of particle filters and gas traps. The shroud is shown in Figure 5-12. It served as a collector and duct to carry the gaseous emissions into the delivery tube to the gaseous-emission storage unit.

Figure 5-13(a) and 5-13(b) show the 2 views of major sheet-metal portions of the disc brake collector (parts were stainless steel to avoid corrosion) and Figure 5-14 shows the entire collector system with the disc brake.

Front and rear views of the collector system, as mounted on the vehicle, are shown in Figures 5-15 and 5-16.

5.5.2 Rotating Seal

5.5.2.1 Initial Design and Problems

The original design of the rubbing seal for the disc brake shroud was a face seal of Teflon (Figure 5-17). Problems arose with this design because of difficulty in realigning the seal after dismantling the shroud for maintenance. When the collector was opened for inspection and then resealed, the out-board shield was not relocated in the exact same position each time. The out-board face was usually slightly cocked in a different manner each time.

The out-board face held the rotating seal. A 1-degree shift of the face cause a 0.060-inch deflection at the groove where the Teflon was sealed. A deflection greater than 0.020 inch was found too great for the seal's Teflon O-ring to make up and consequently nonreproducible sealing and leaking occurred.

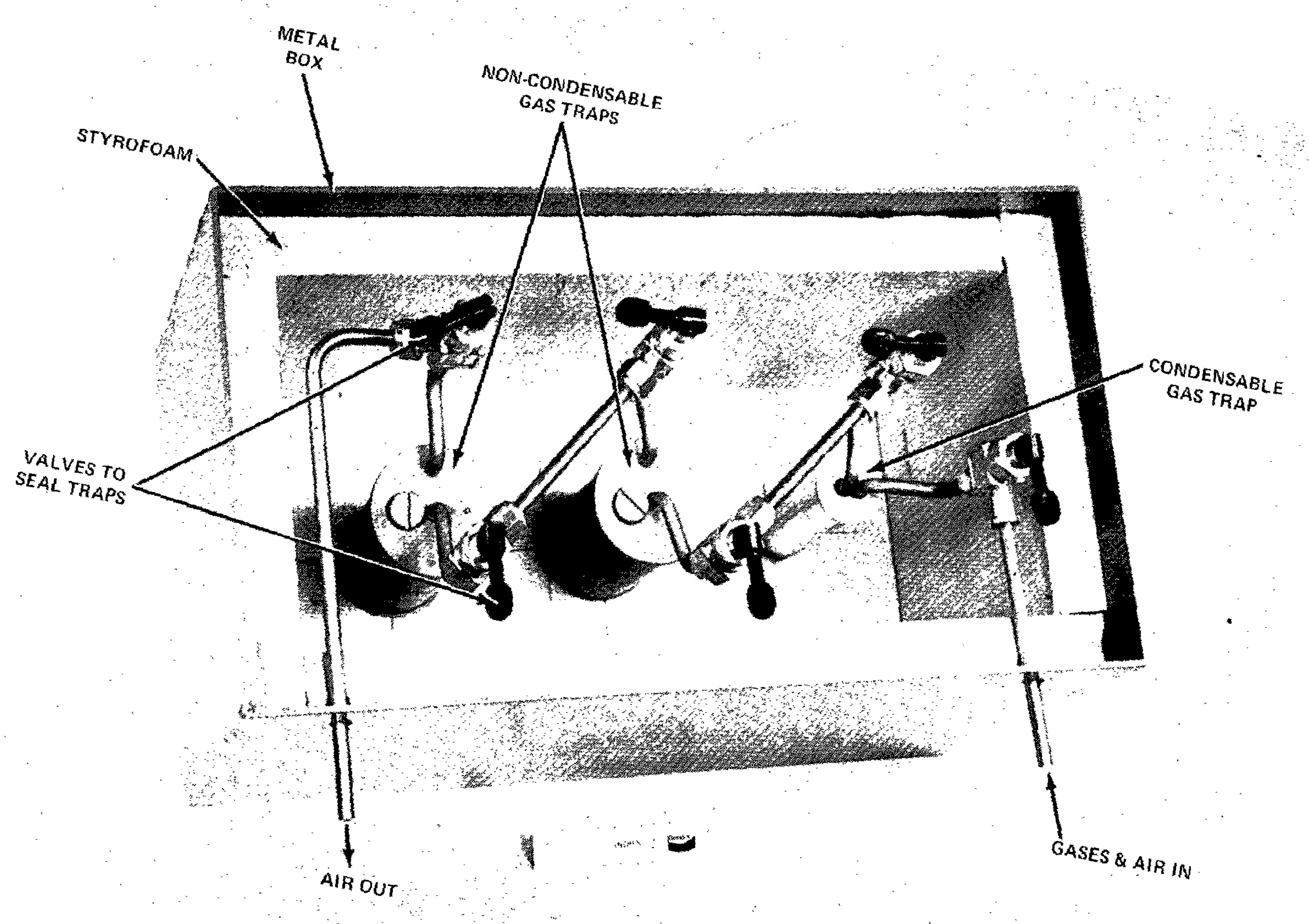


Figure 5-11 - Gas Collection System

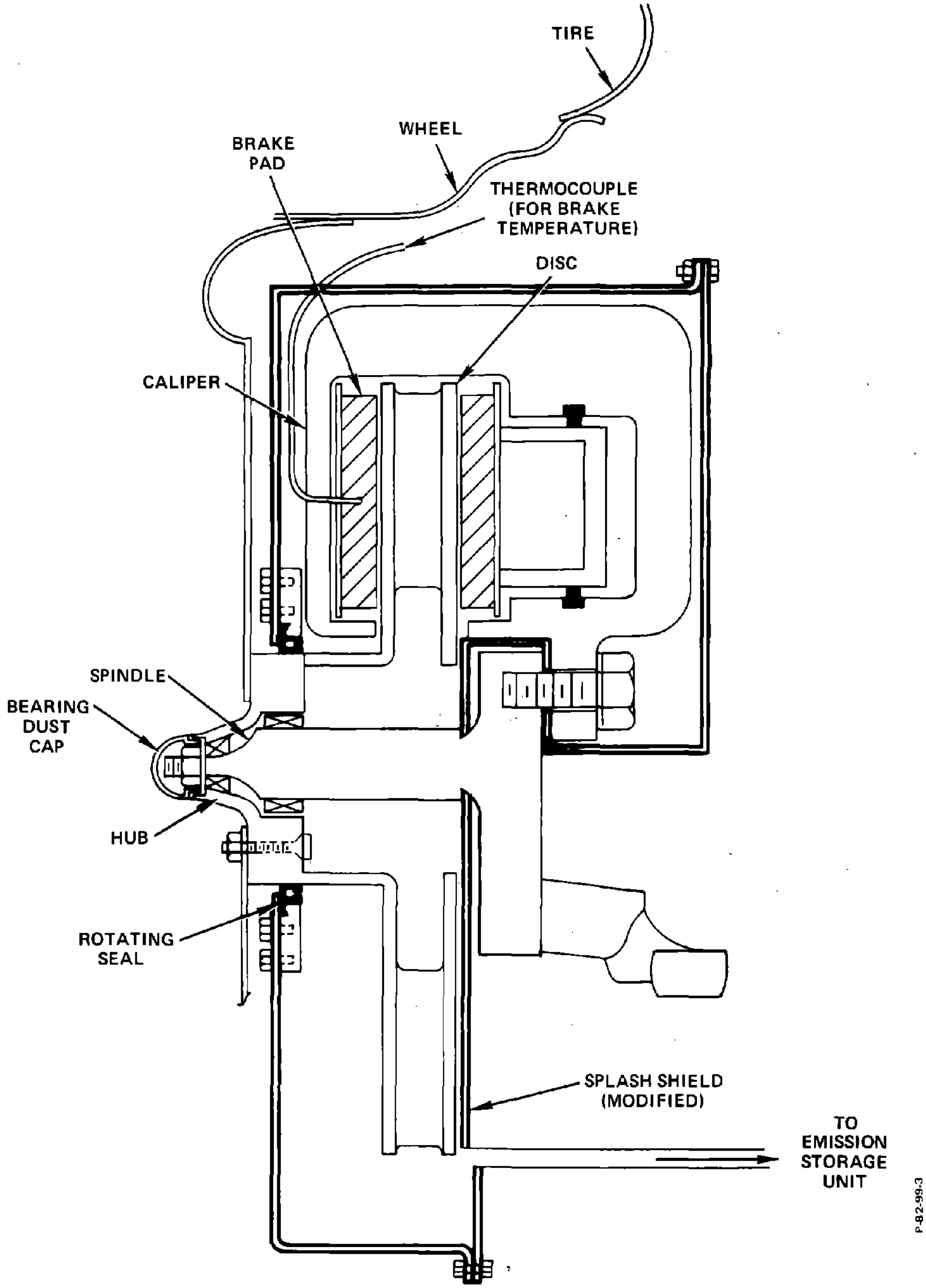


Figure 5-12 - Sectional View - Disc Brake Shroud

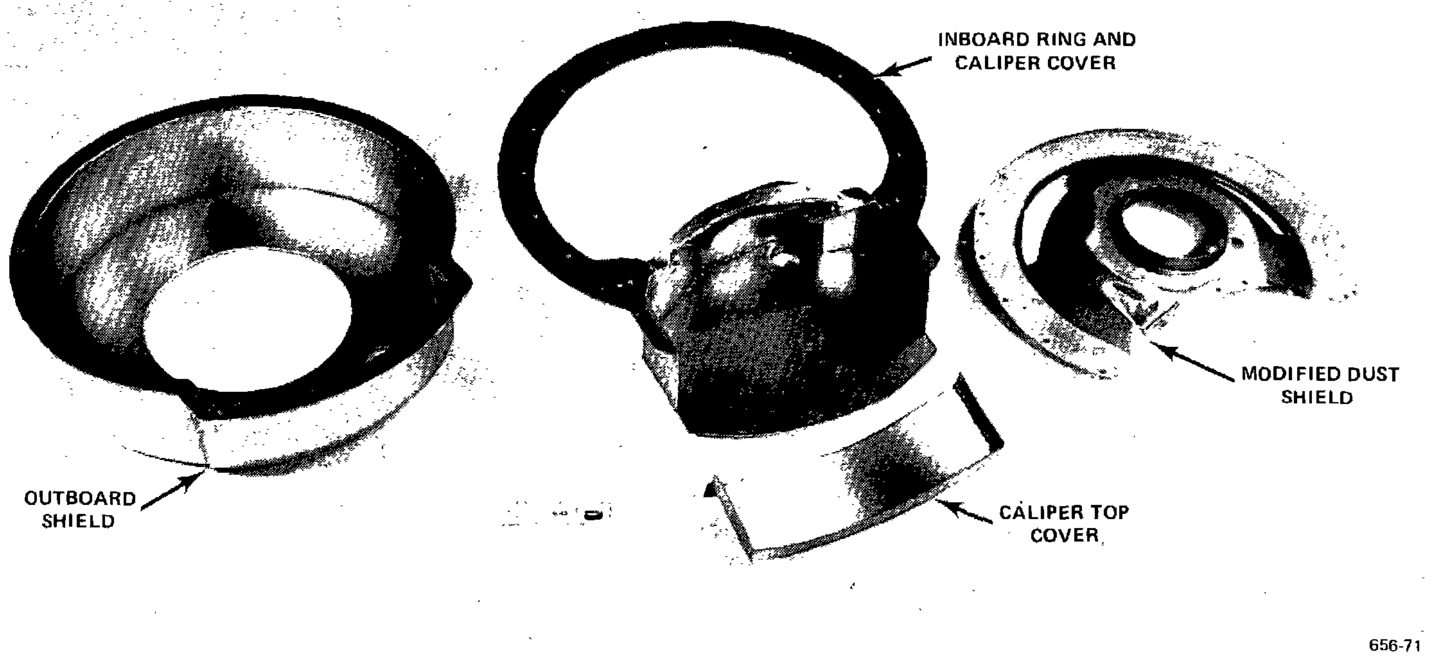


Figure 5-13(a) - Major Portions of Disc Brake Emission Collector Assembly

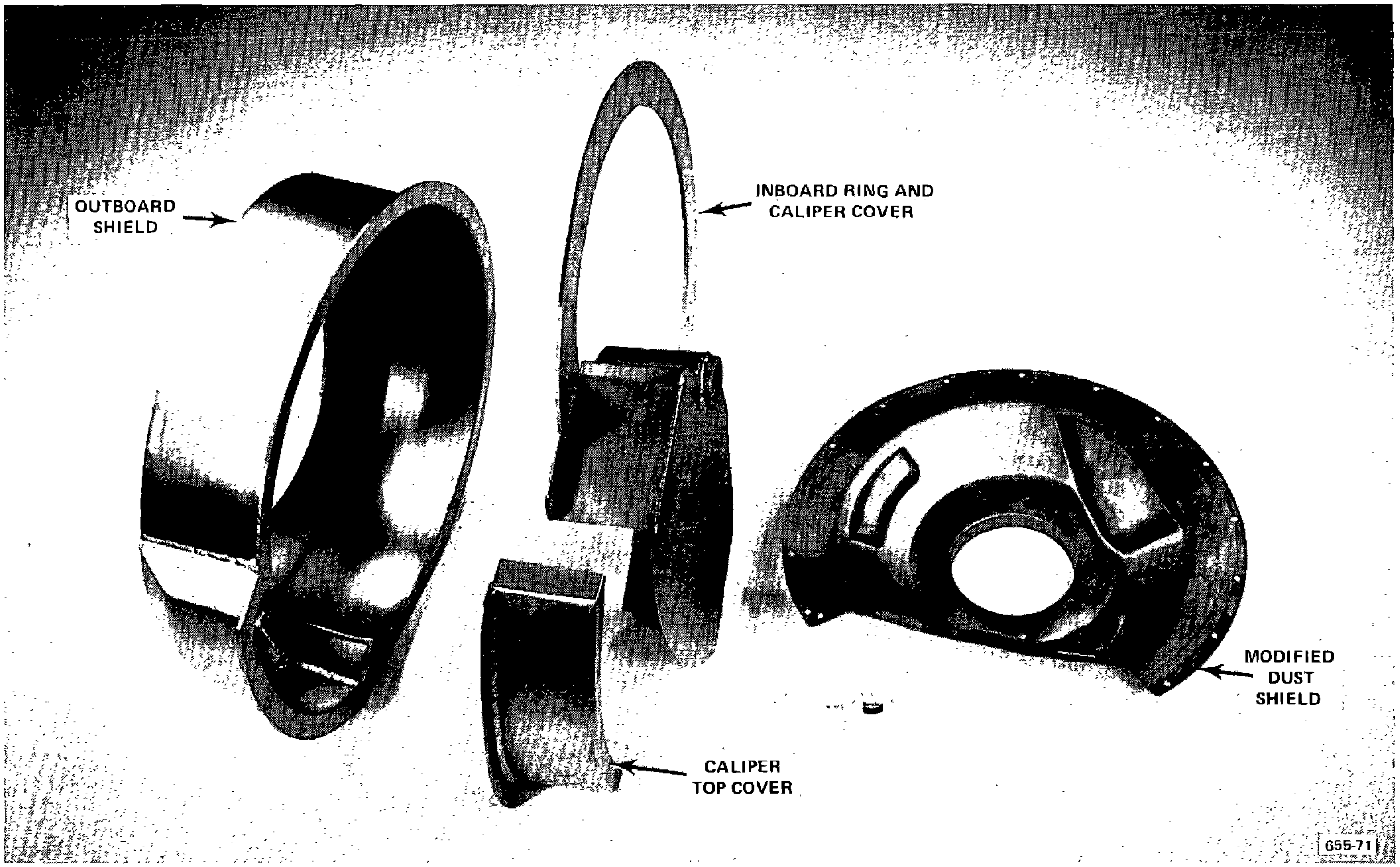


Figure 5-13(b) - Major Portions of Disc Brake Emission Collector Assembly

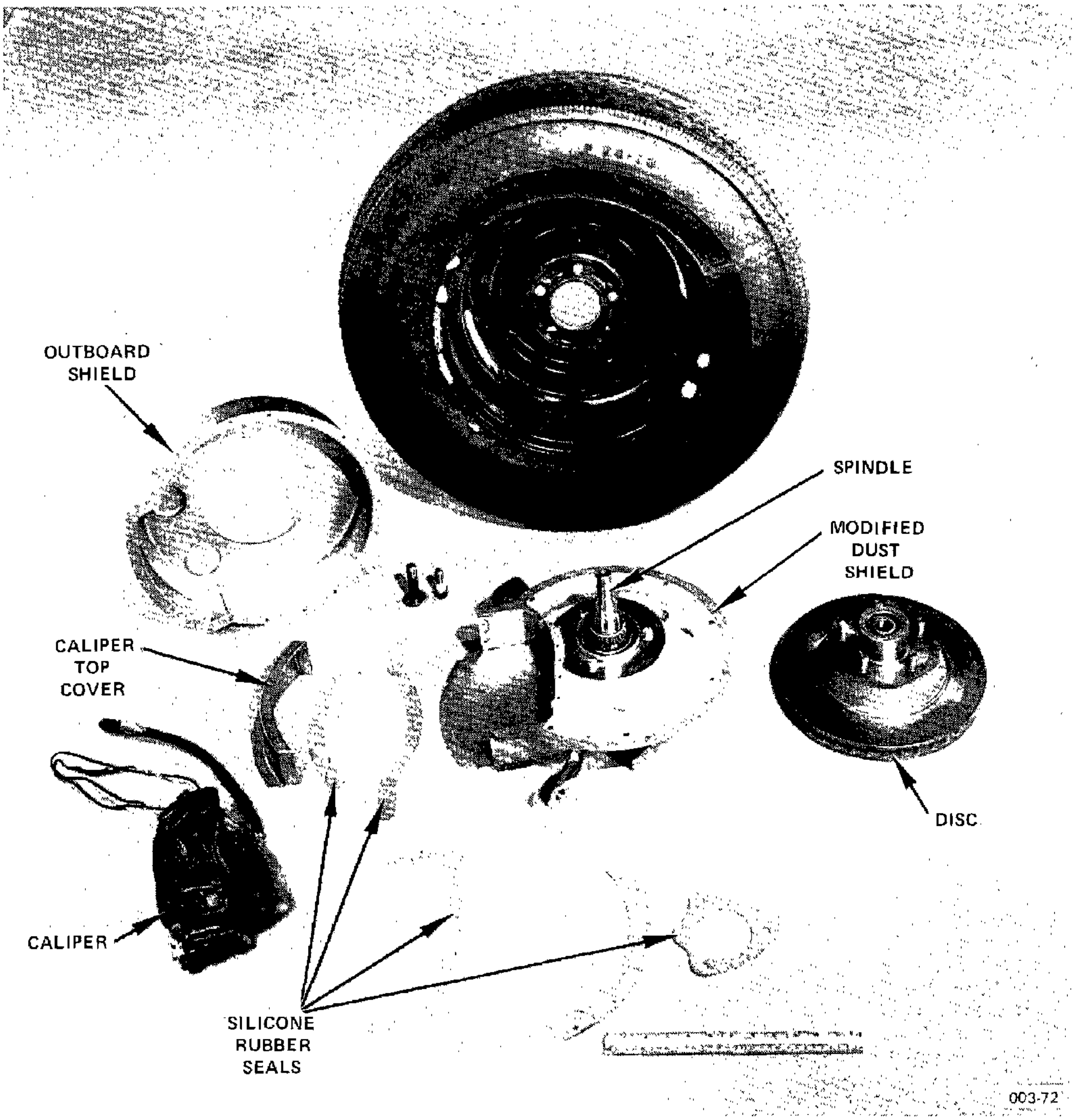


Figure 5-14 - Disc Brake Emission Collector Assembly - Exploded View

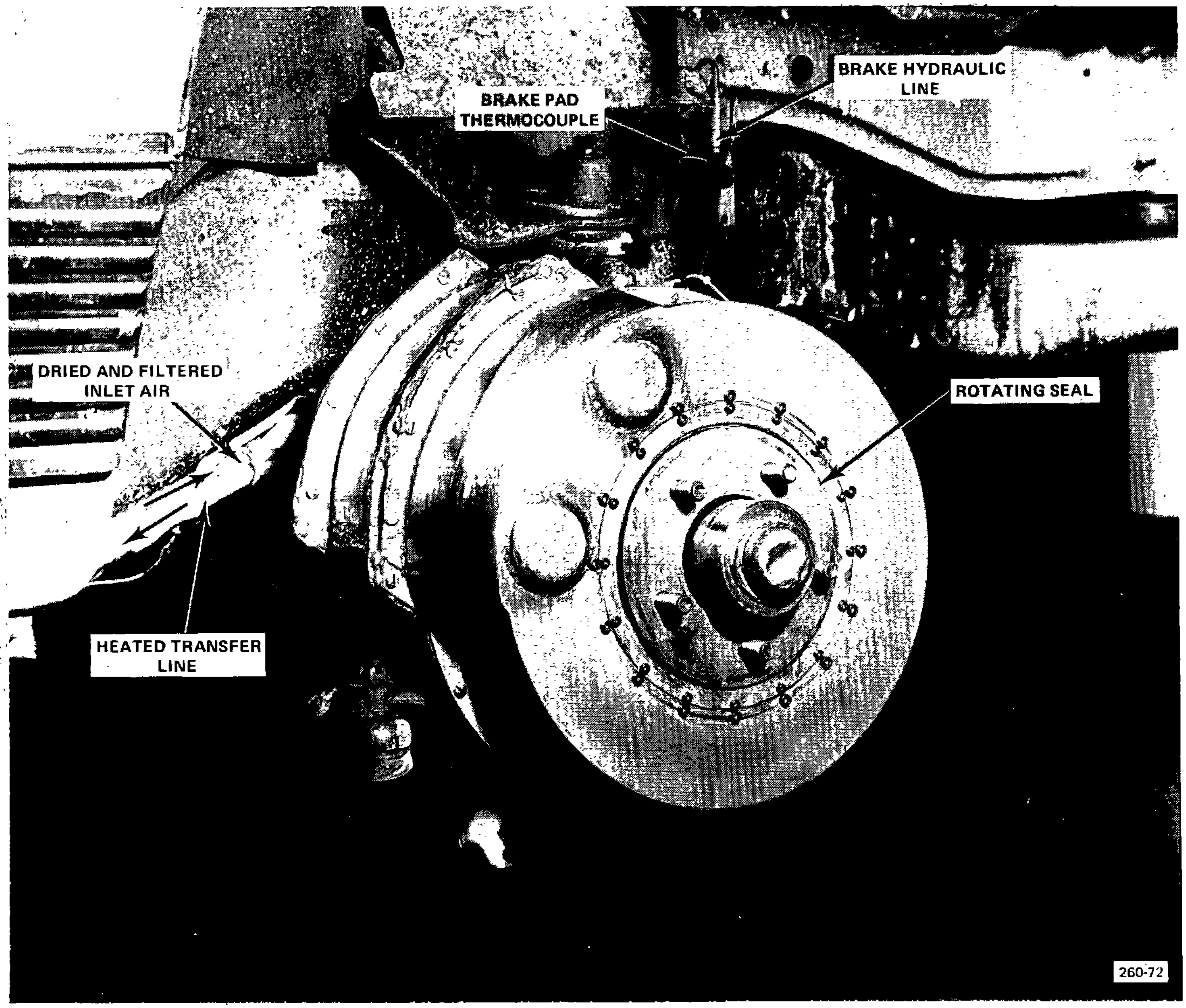


Figure 5-15 - Front Disc Brake Emission Collector Installed on Vehicle

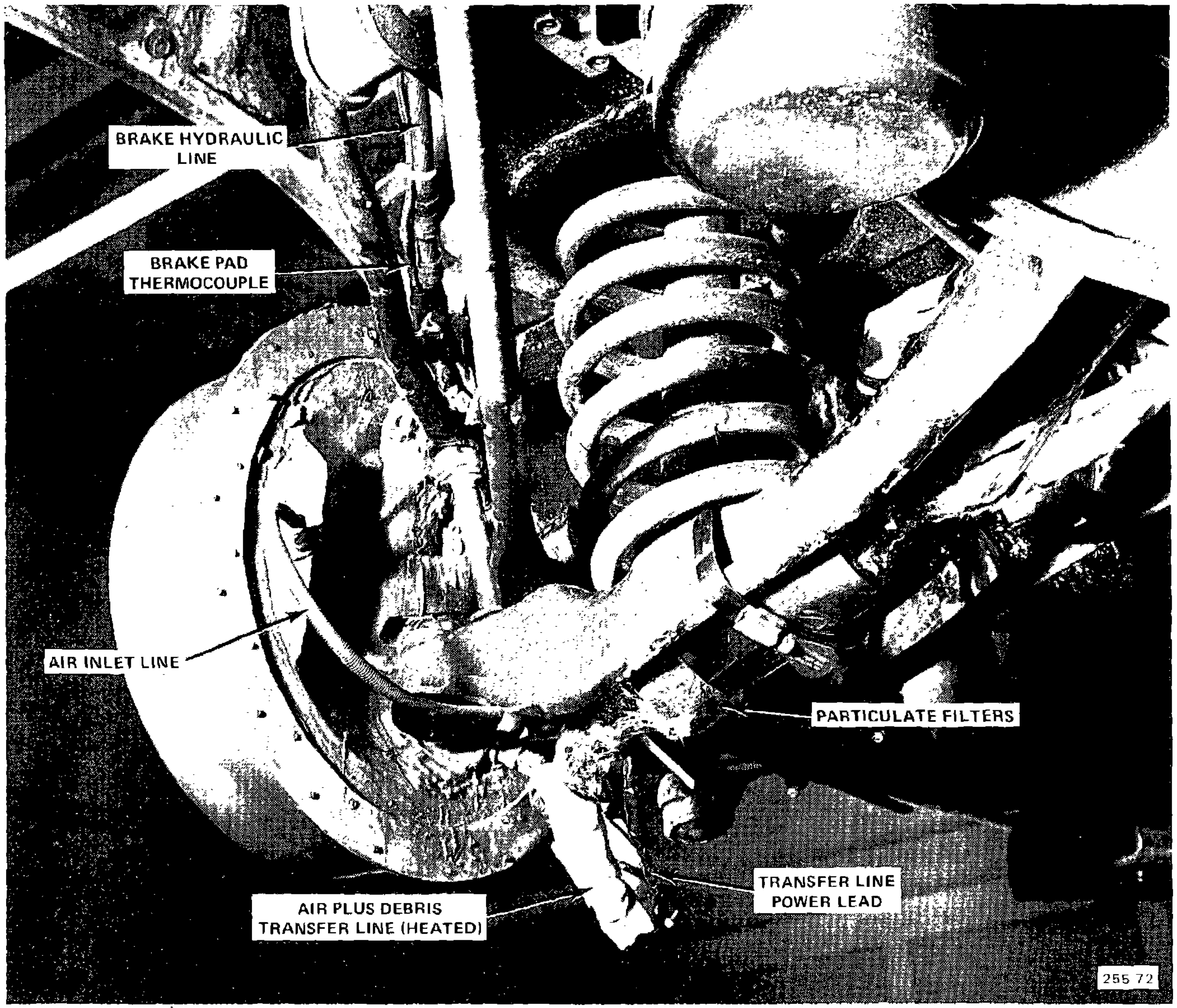


Figure 5-16 - Back View of Front Disc Brake Emissions Collector Showing Instrumentation

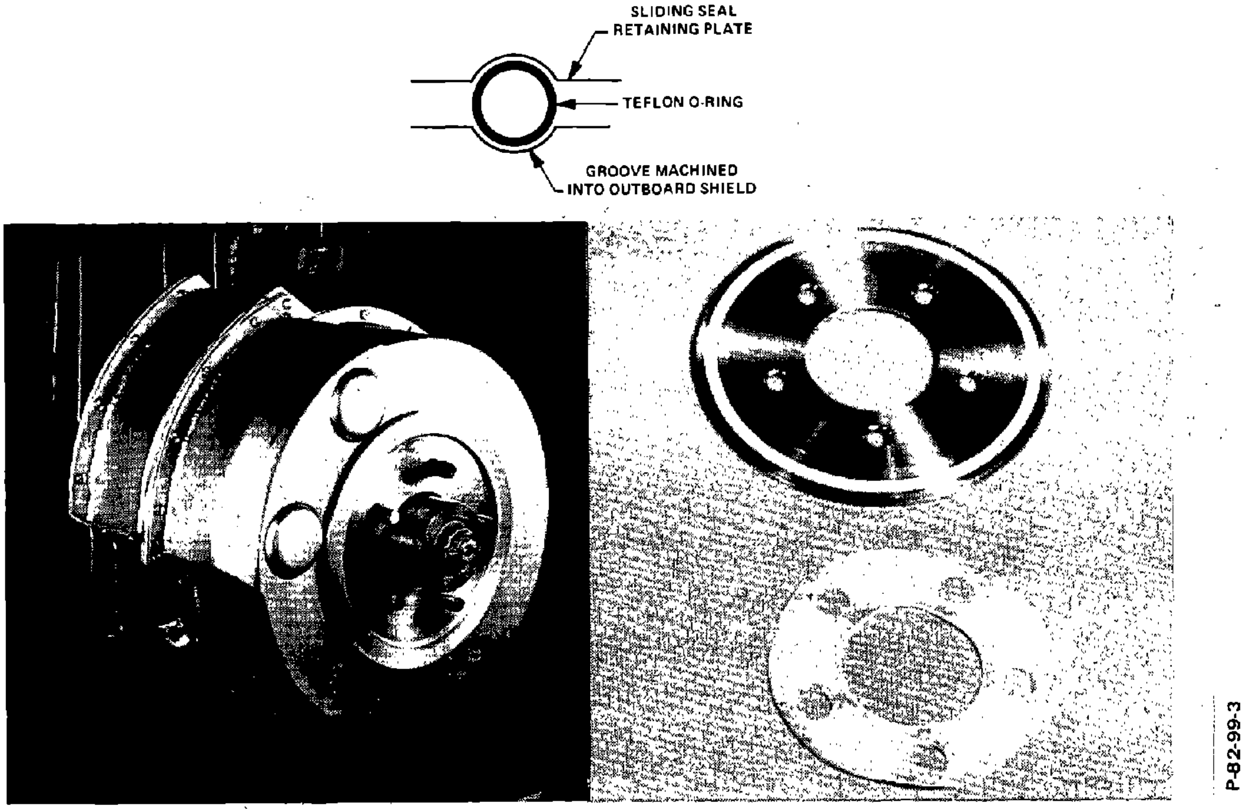


Figure 5-17 – Initial Design (MKI) for Rotating Seal of Disc Brake Collector

5.5.2.2 Final Design

A new sealing system was designed, using a shaft-type spring-loaded seal, of commercial manufacture, made of graphite-filled Teflon. Figure 5-18 shows the drawing of the sealing system and Figure 5-19 shows the details at the sealing surface.

5.5.3 Thermal Control Aids

During preliminary testing, it was apparent that the shrouded disc brake was running measureably hotter than the unshrouded disc brake. Therefore, various cooling aids were devised to reduce this temperature differential. Three cooling aids were used:

(1) Black oxide coating of the shroud to improve heat radiation.

(2) Water sprinkling system connected to the windshield washer pump for cooling.

(3) Open or mag-type wheel for improved convective cooling of the shroud.

These additions are shown in Figures 5-20 and 5-21.

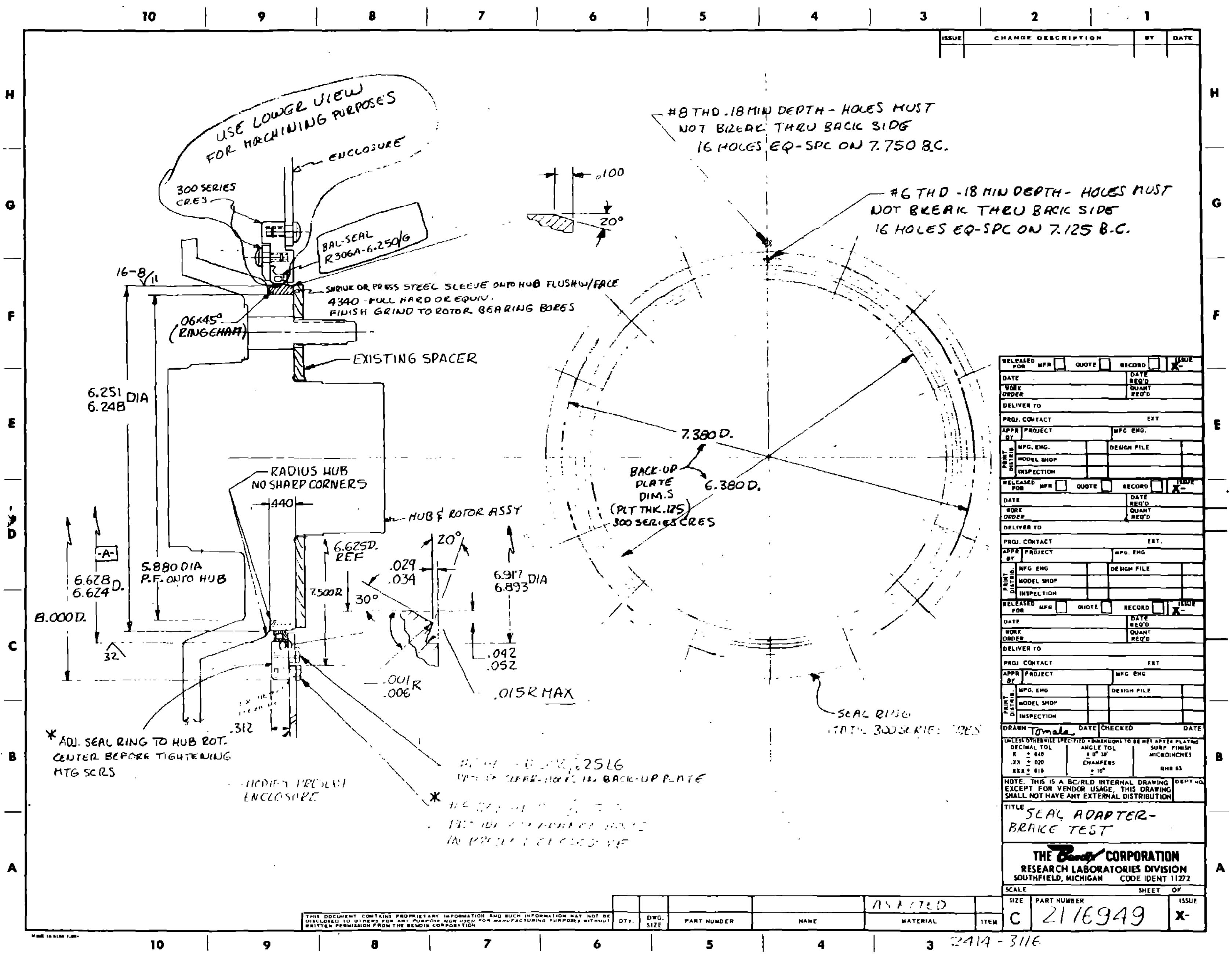


Figure 5-18 - Rotating Seal for Disc Brake Emission Collector

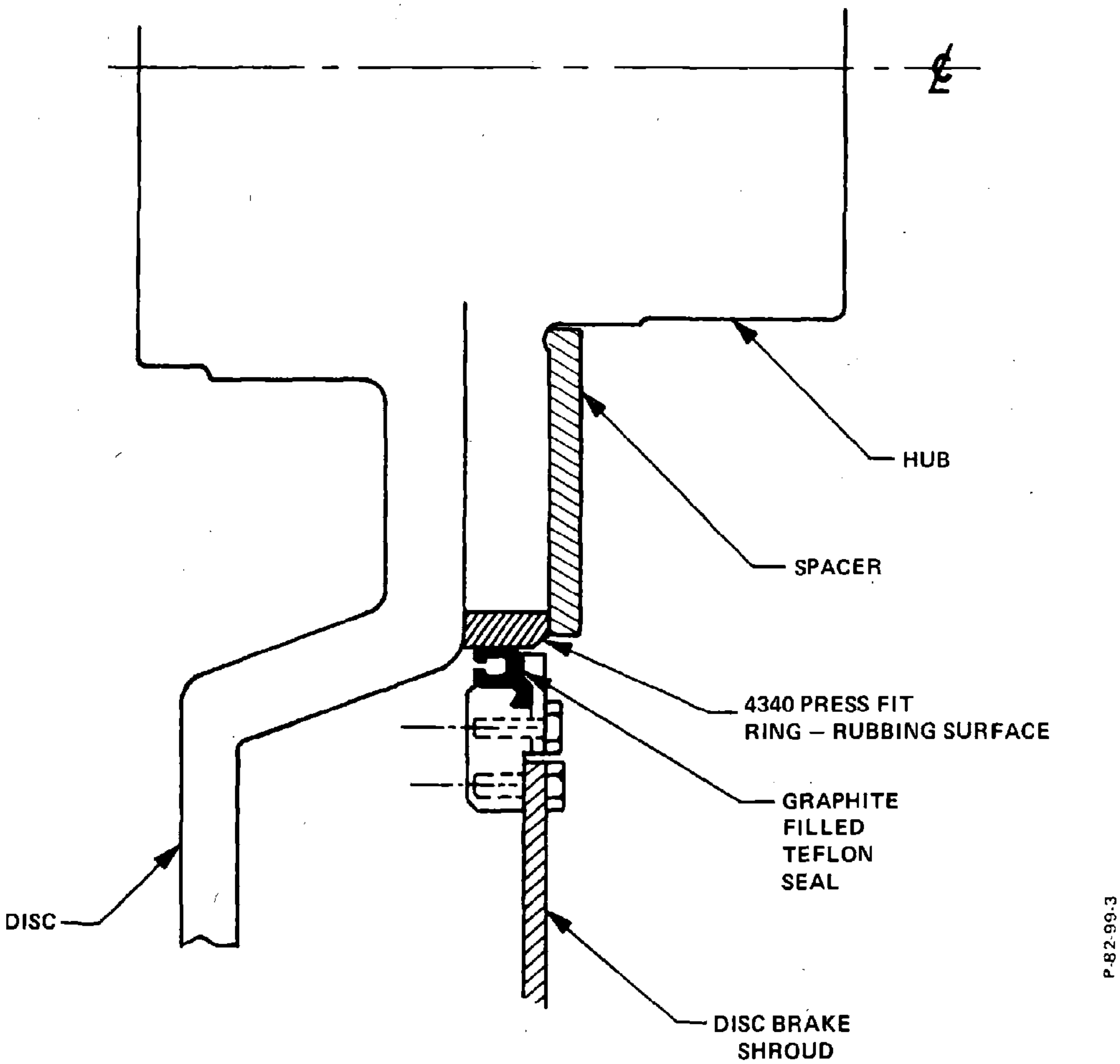


Figure 5-19 - Details of Disc Brake Collector Rotating Seal

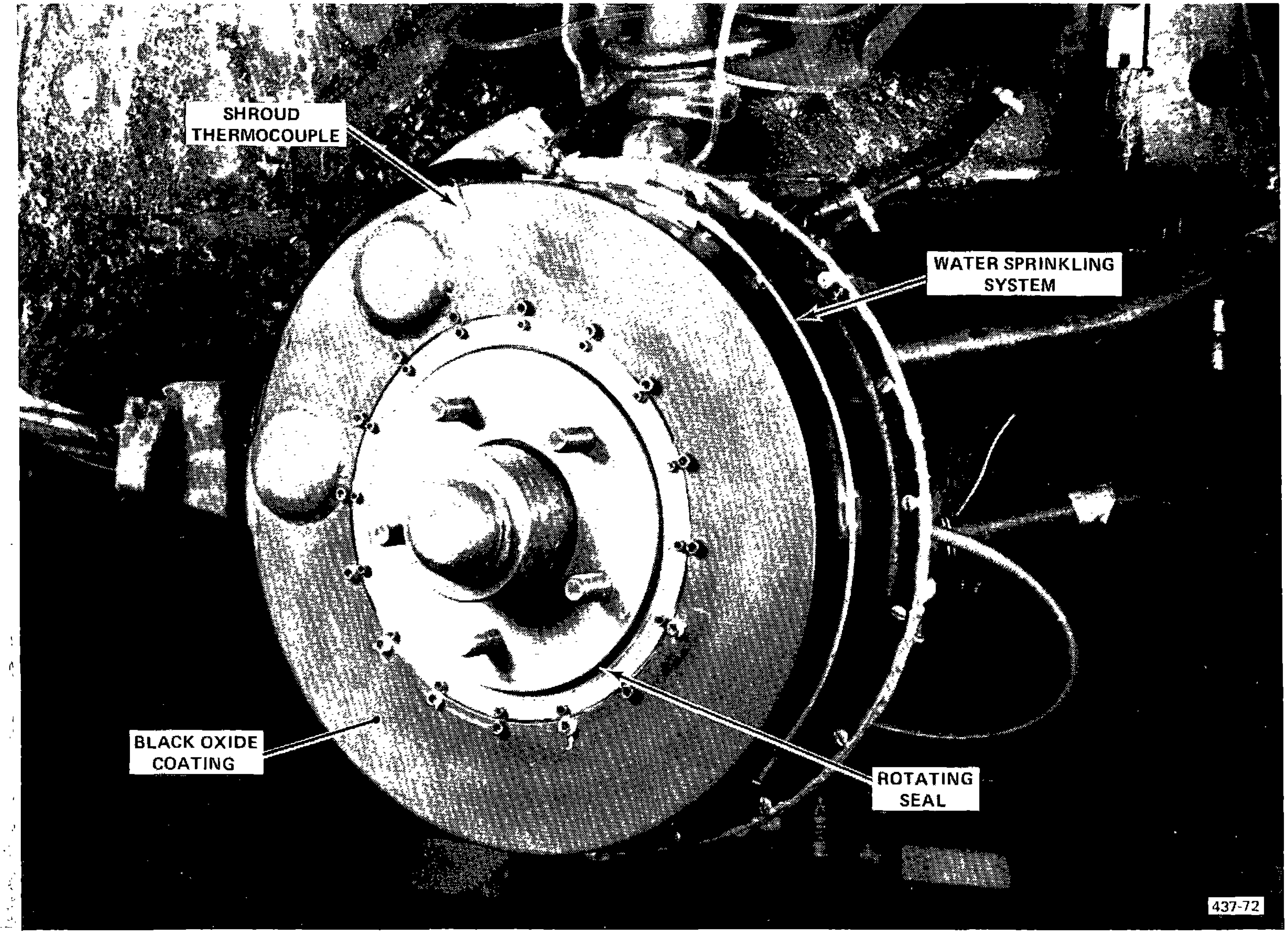


Figure 5-20 - Front Disc Brake Emissions Collector Showing Thermal Control Aids

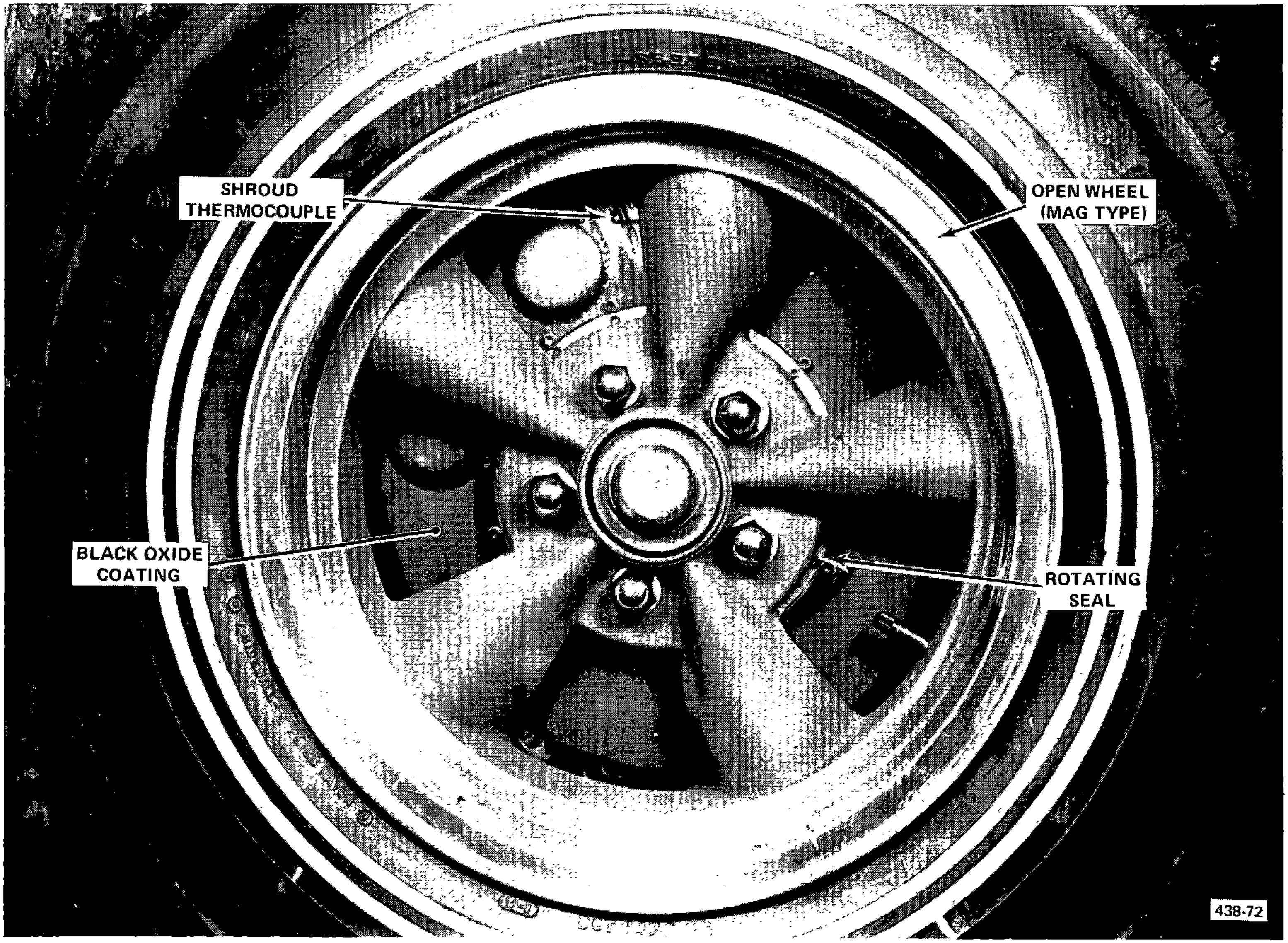


Figure 5-21 - Right Front Wheel of Test Vehicle

5.6 DRUM BRAKE COLLECTOR

5.6.1 Initial Designs and Rotating-Seal Problems

The original concept for the sample collector on the right rear collector was planned such that the drum and backing plate formed the shroud along with a rotating seal. This approach was used in order to minimize changes to the cooling efficiency of the drum.

The first design concept (MKI) was a face seal of Teflon kept in contact with the polished edge of the backing plate by a silicone rubber O-ring (see Figure 5-22). This seal had a short service life, because of alignment problems and the high rubbing speeds.

The second design concept again attempted, to use the backing plate and drum as the major components of the shroud. However, this design (MKII) incorporated a shaft-type spring-loaded seal, of commercial manufacture, made of graphite-filled Teflon. The seal manufacturer indicated that this seal could sustain the rubbing speeds and temperatures involved (2000 ft/min and 400°F). This seal design is shown in Figure 5-23. Figure 5-24 shows the modified backing plate and drum made from this design. Figures 5-25 and 5-26 show front and rear views of the system as mounted on the vehicle. The seal in this system failed

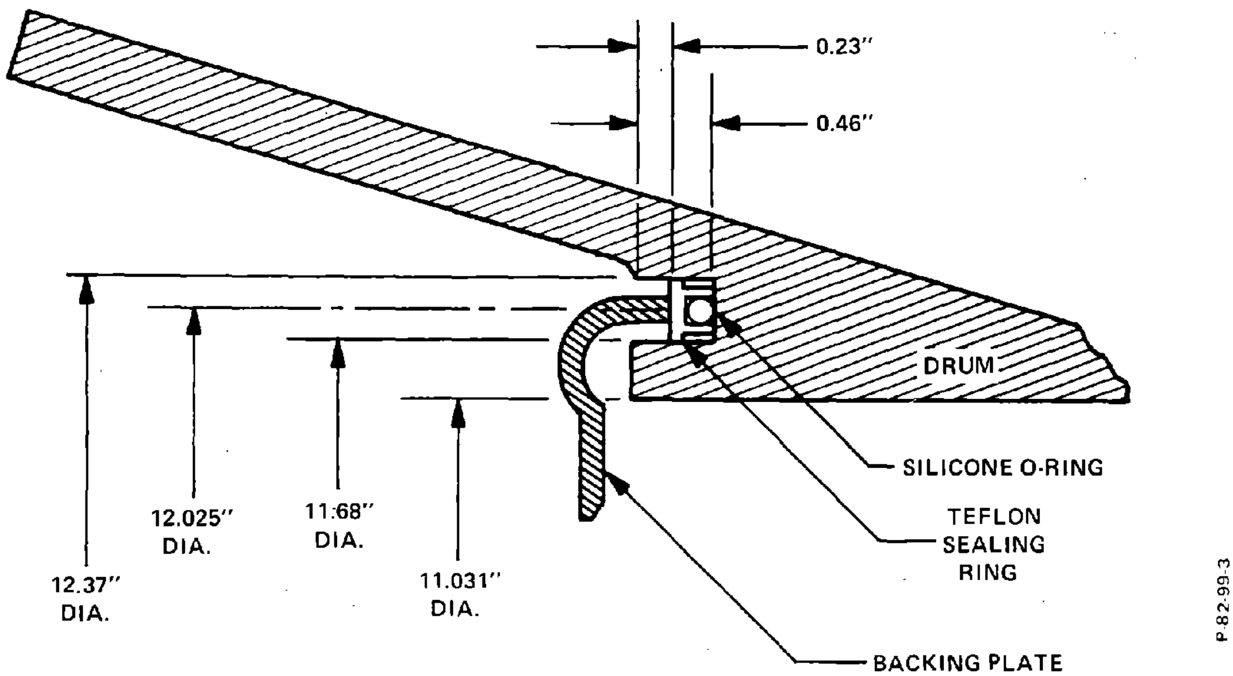


Figure 5-22 - First Seal Design (MKI) for Drum Brake

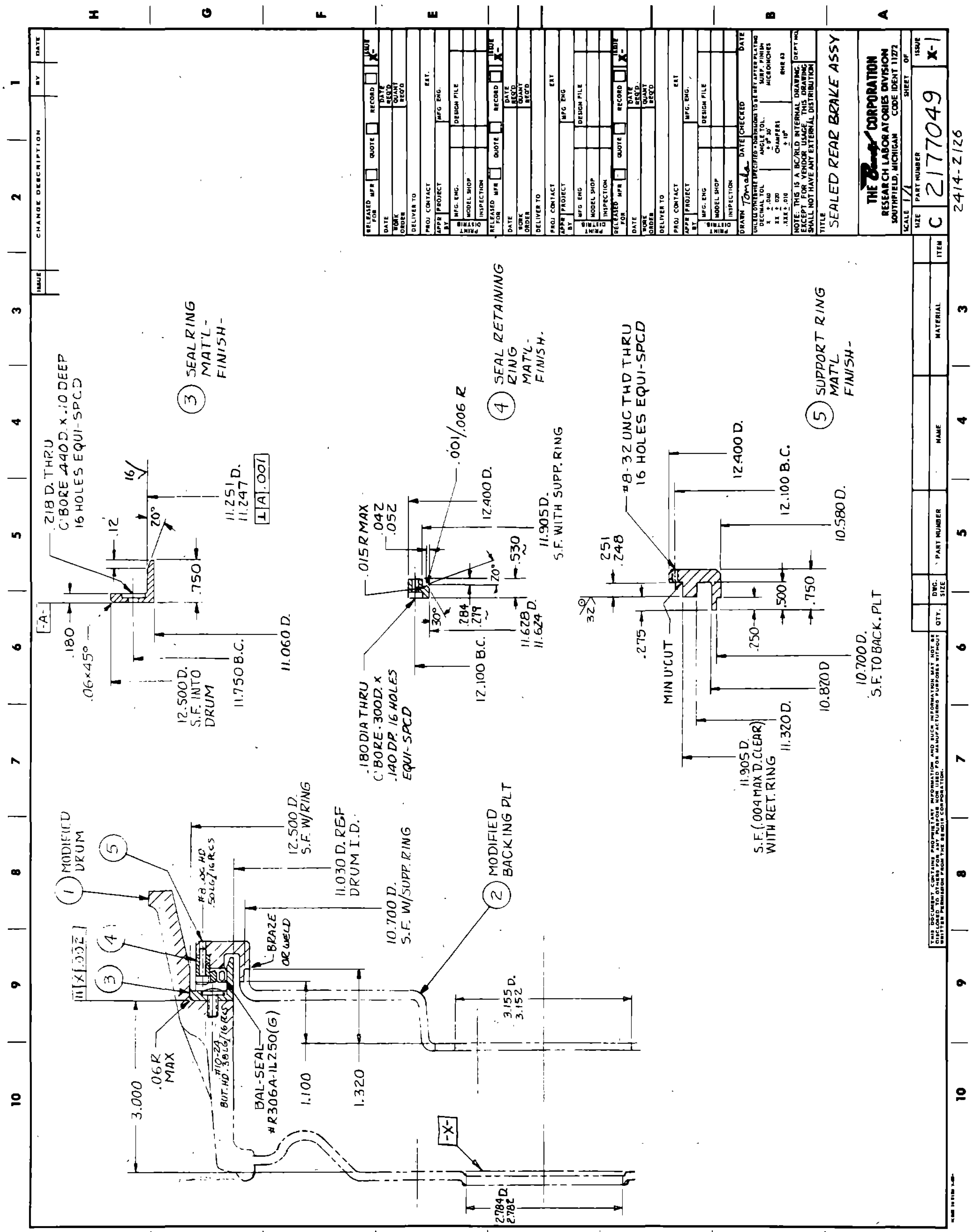
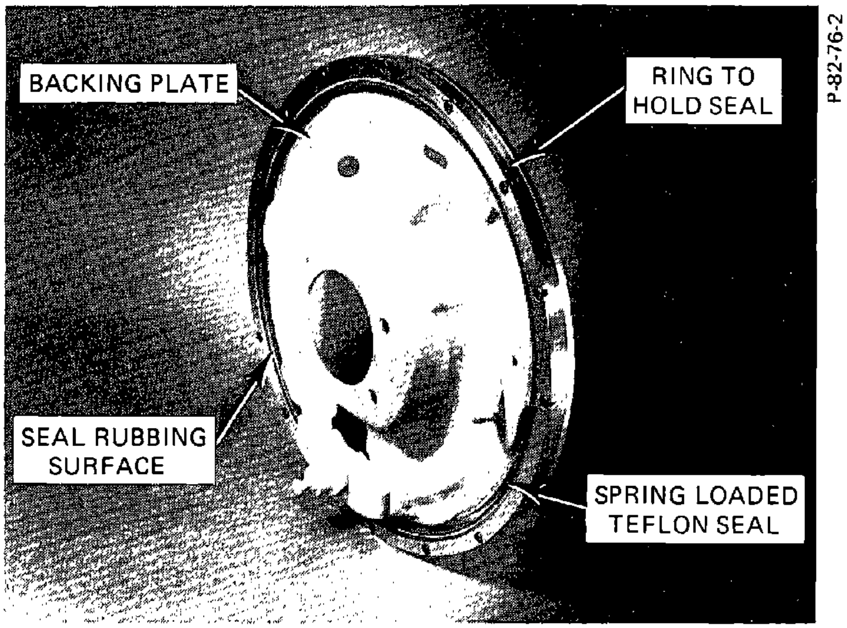
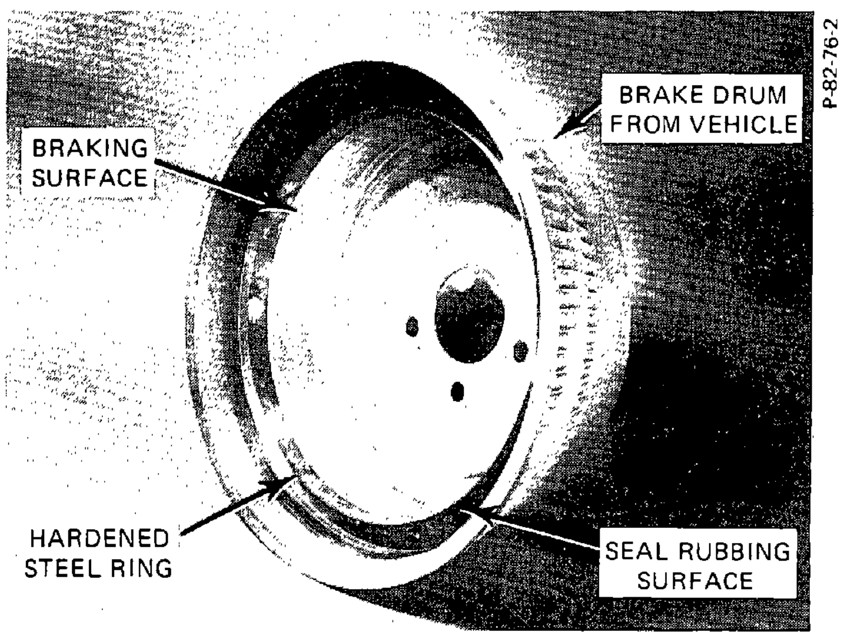


Figure 5-23 - MKII Rotating Seal for Drum Brake Emission Collector



(a) Modified Rear Brake Drum Backing Plate Showing Spring-Loaded Teflon Seal



(b) Modified Rear Brake Drum Showing Hardened Steel Ring for Rotating Seal

Figure 5-24 - Details of MKII Rotating Seal

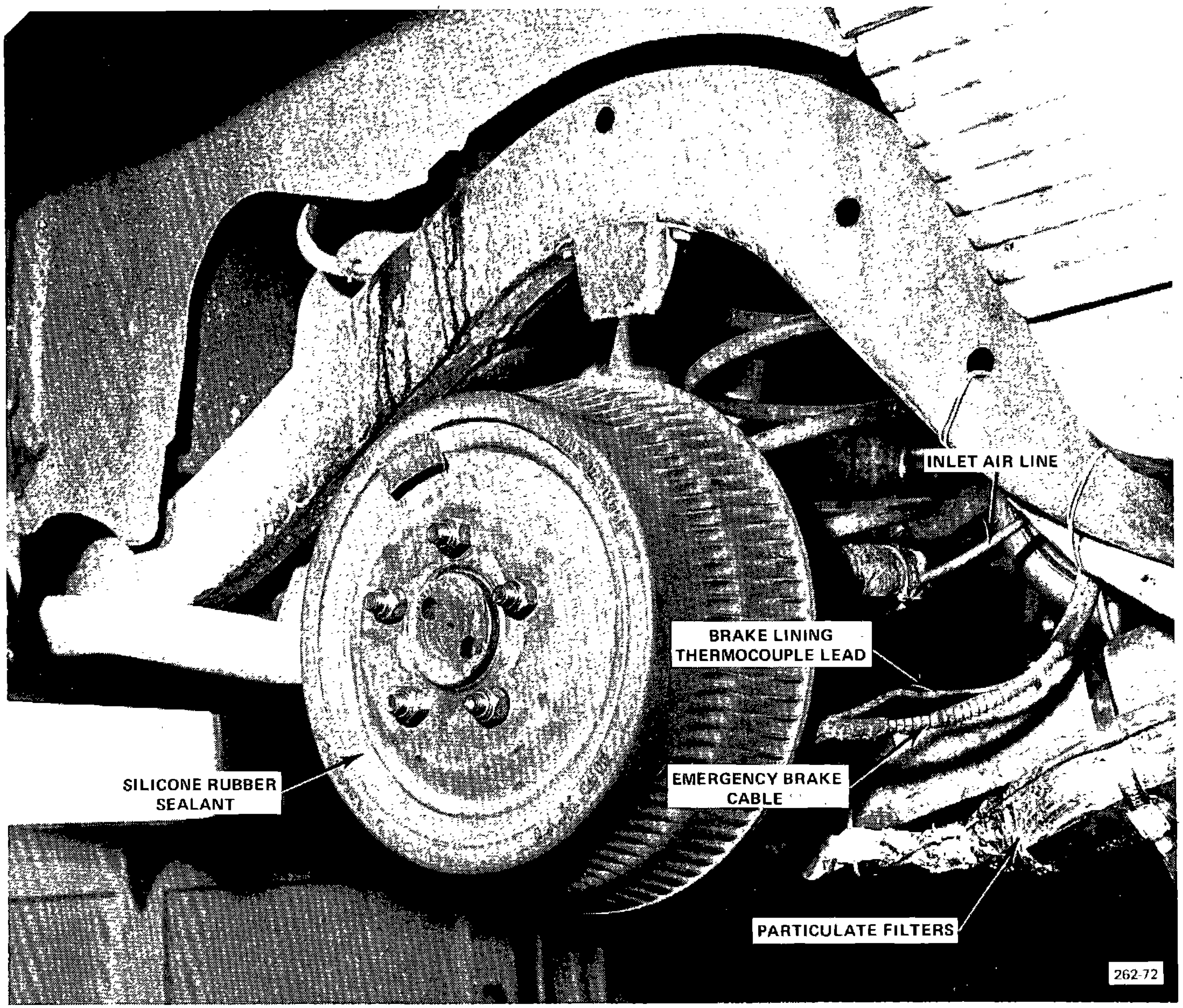


Figure 5-25 - Rear Drum Brake Emission Collector after a short time as shown in Figure 5-27. On investigating the failure, three major problems were found:

(1) High interface speeds (1450 ft/min at 40 mph).

(2) Increase in seal interface pressure because of lack of concentricity and expansion of the drum.

(3) Heat input to the seal from the braking action and distortion of the drum from the braking action.

5.6.2 Final Design

In order to correct the problems described above, a third seal design (MKIII) was developed. This design removed the rubbing seal from the drum to the axle housing area, decreased the diameter (and thus the rubbing speed) of the seal and improved concentricity by using accurate alignment of components and by modifying the rear axle hub to align the drum concentric to the axle bearings within 0.001 inch. A tapered lead was used on the axle hub to facilitate mounting of the drum. This design is shown in Figure 5-28. An outboard view of this sytem without the drum is shown in Figure 5-29. Outboard and inboard views of the assembled system are shown in Figures 5-30 and 5-31. This is the system which was used in all testing.

5.7 CLUTCH COLLECTOR

The clutch collector system consisted mainly of a filtered air inlet and an outlet to the sample storage system with all other external holes sealed. A schematic of the system is shown in Figure 5-32 and a photograph of the system installed is shown in Figure 5-33.

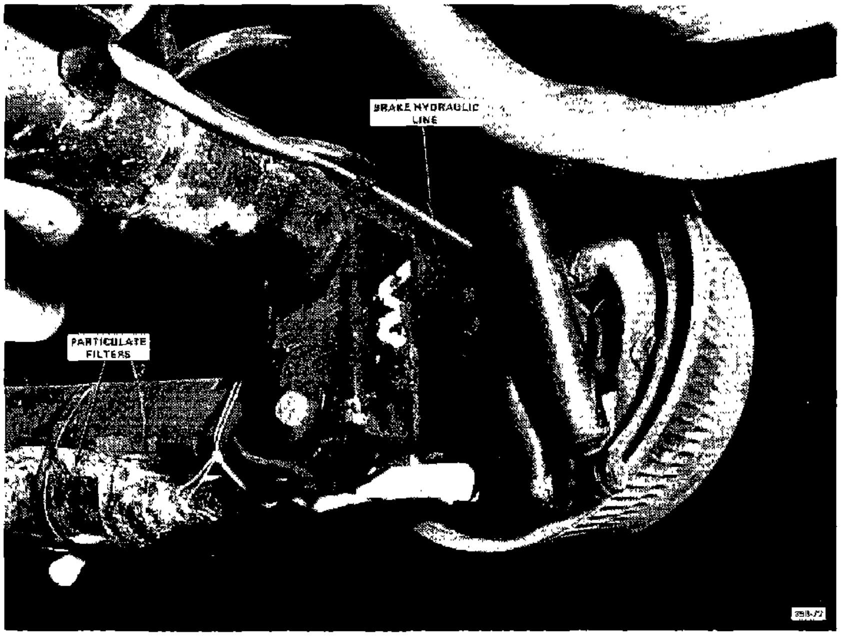


Figure 5-26 - Rear View of Rear Drum Brake Emissions Collector Showing Instrumentation

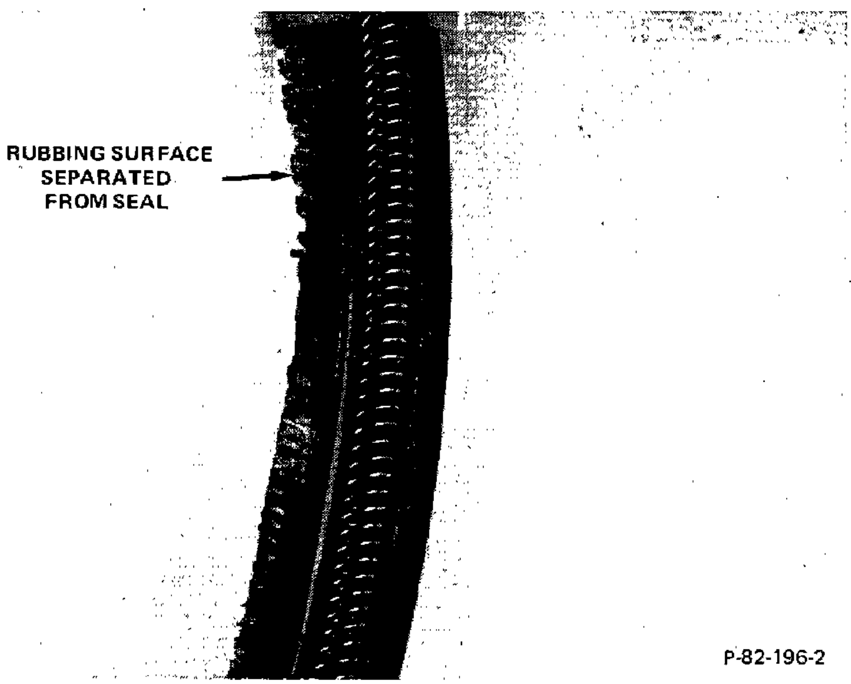


Figure 5-27 - Completely Worn Seal from MKII Rear Drum Brake Collector

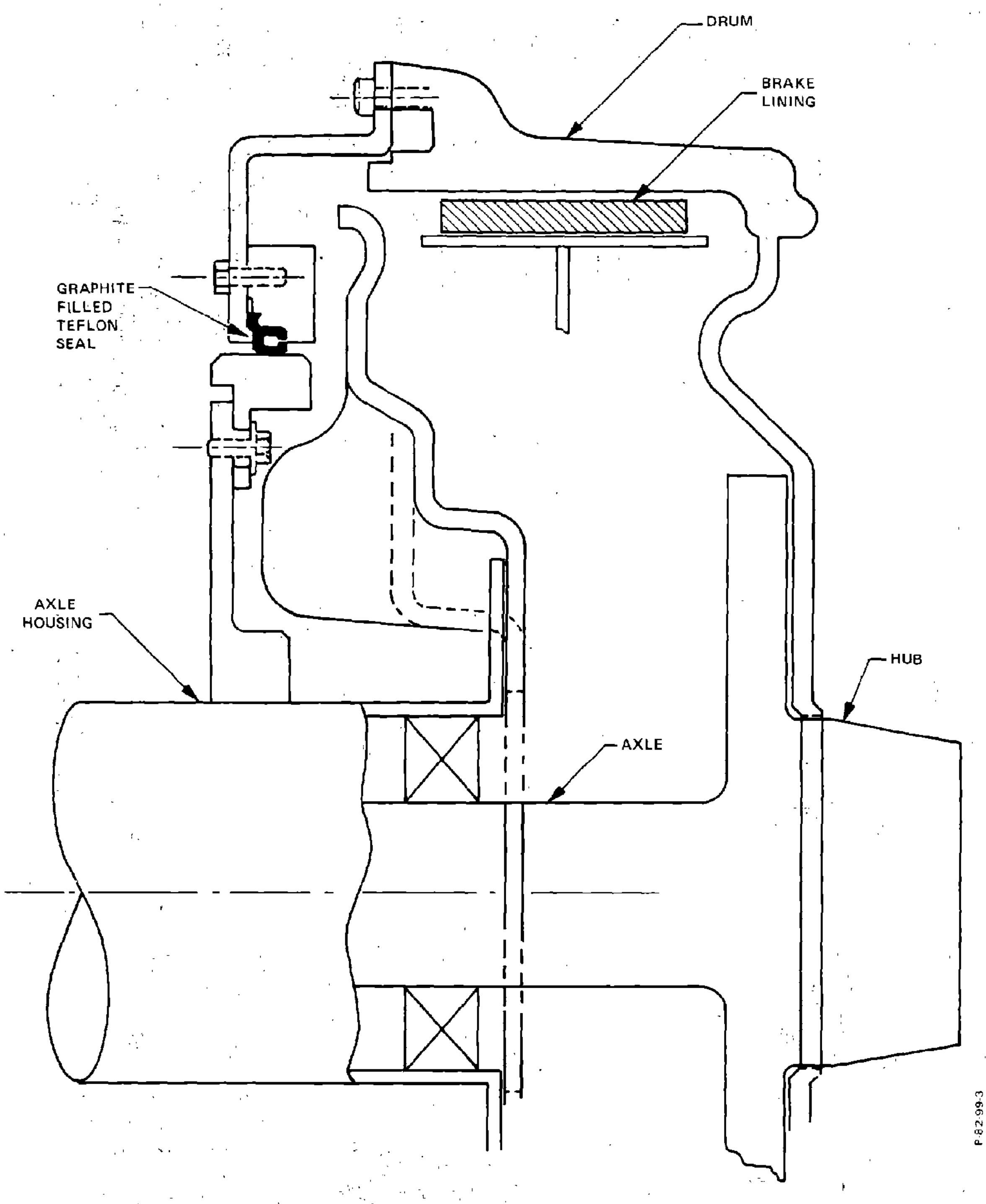


Figure 5-28 - Sectional View of Drum Brake Shroud (MKIII)

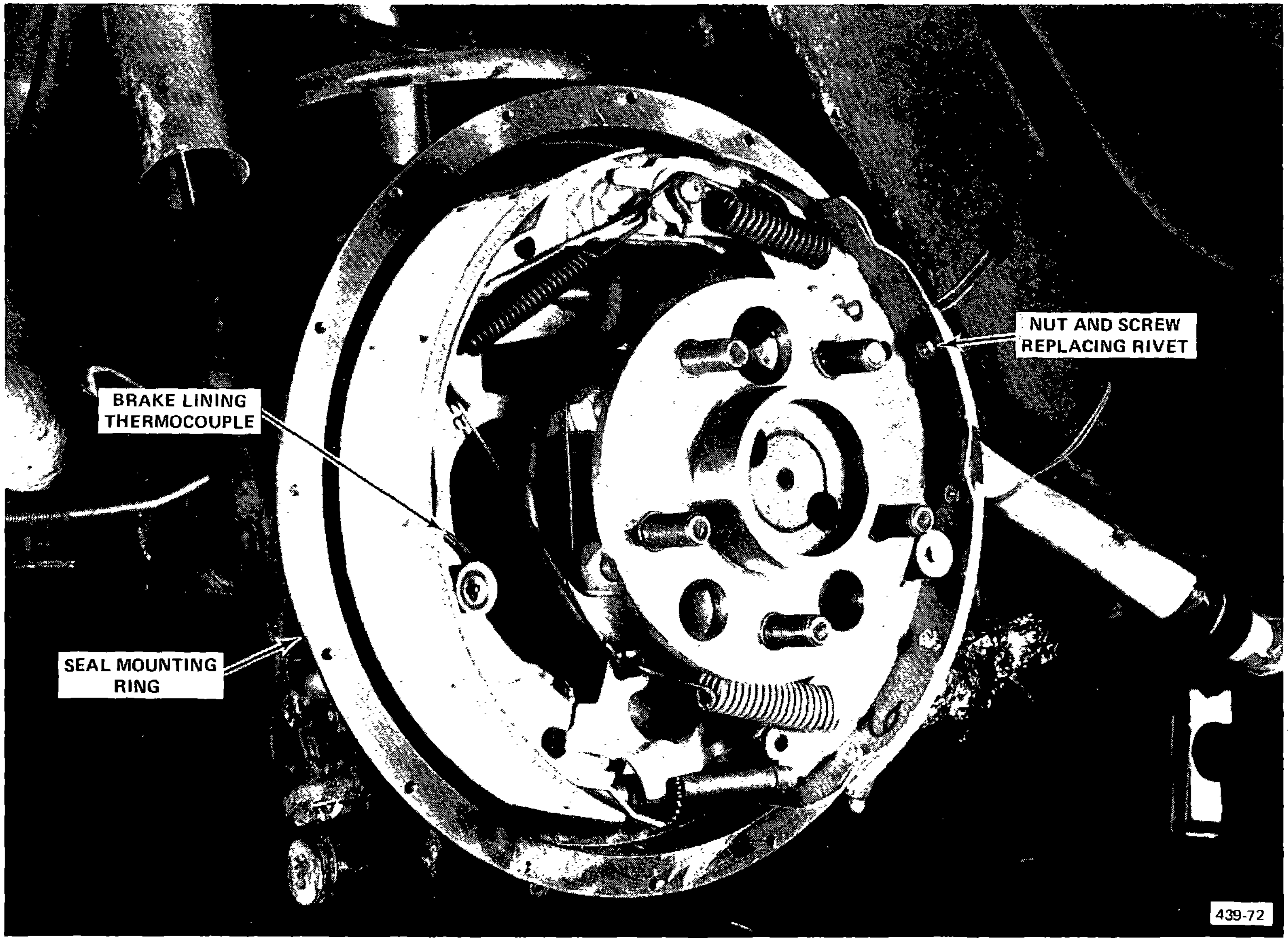


Figure 5-29 - Outboard View of Rear Drum Brake Emissions Collector Interior

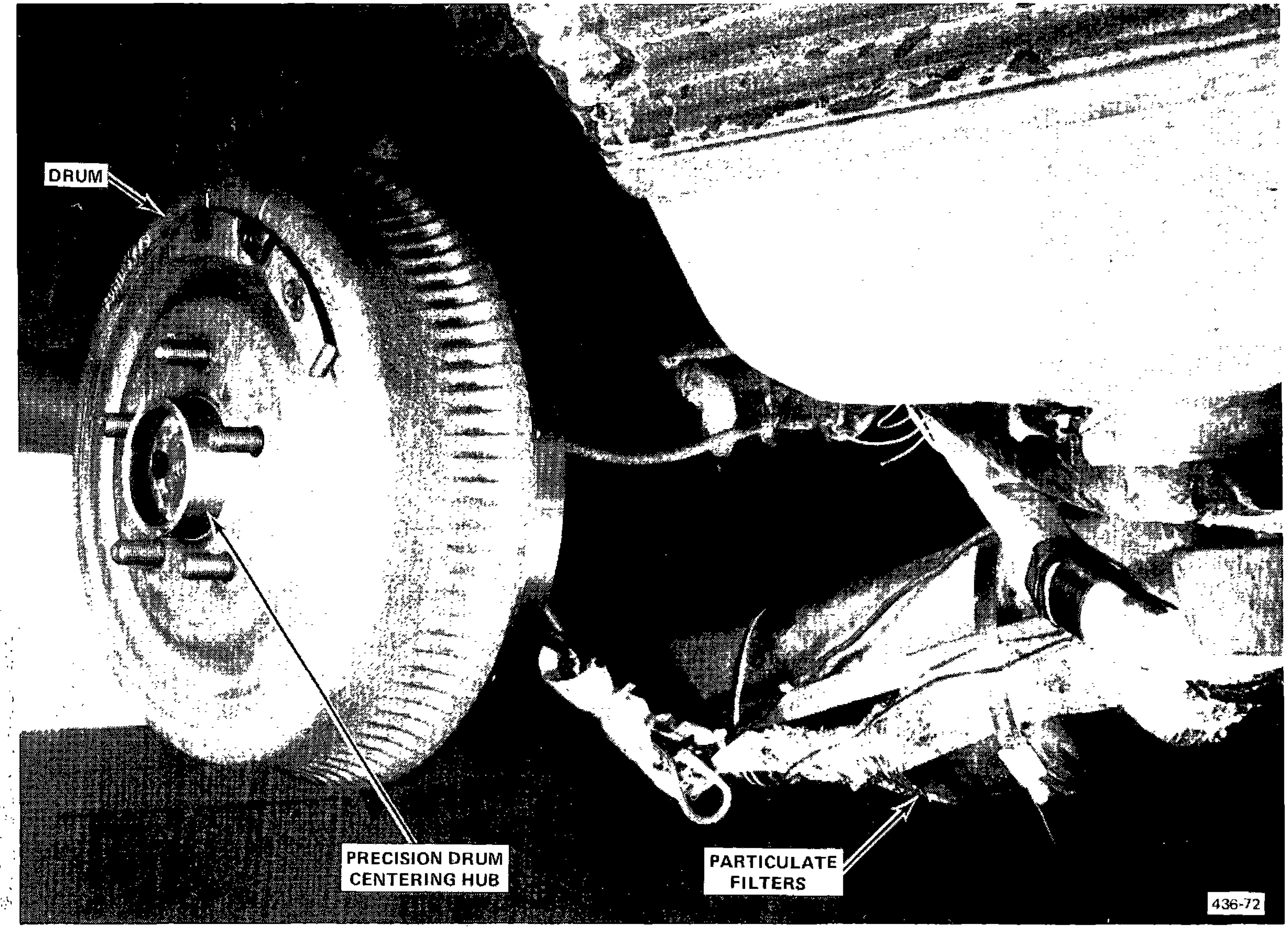


Figure 5-30 - Assembled Rear Drum Brake Emissions Collector

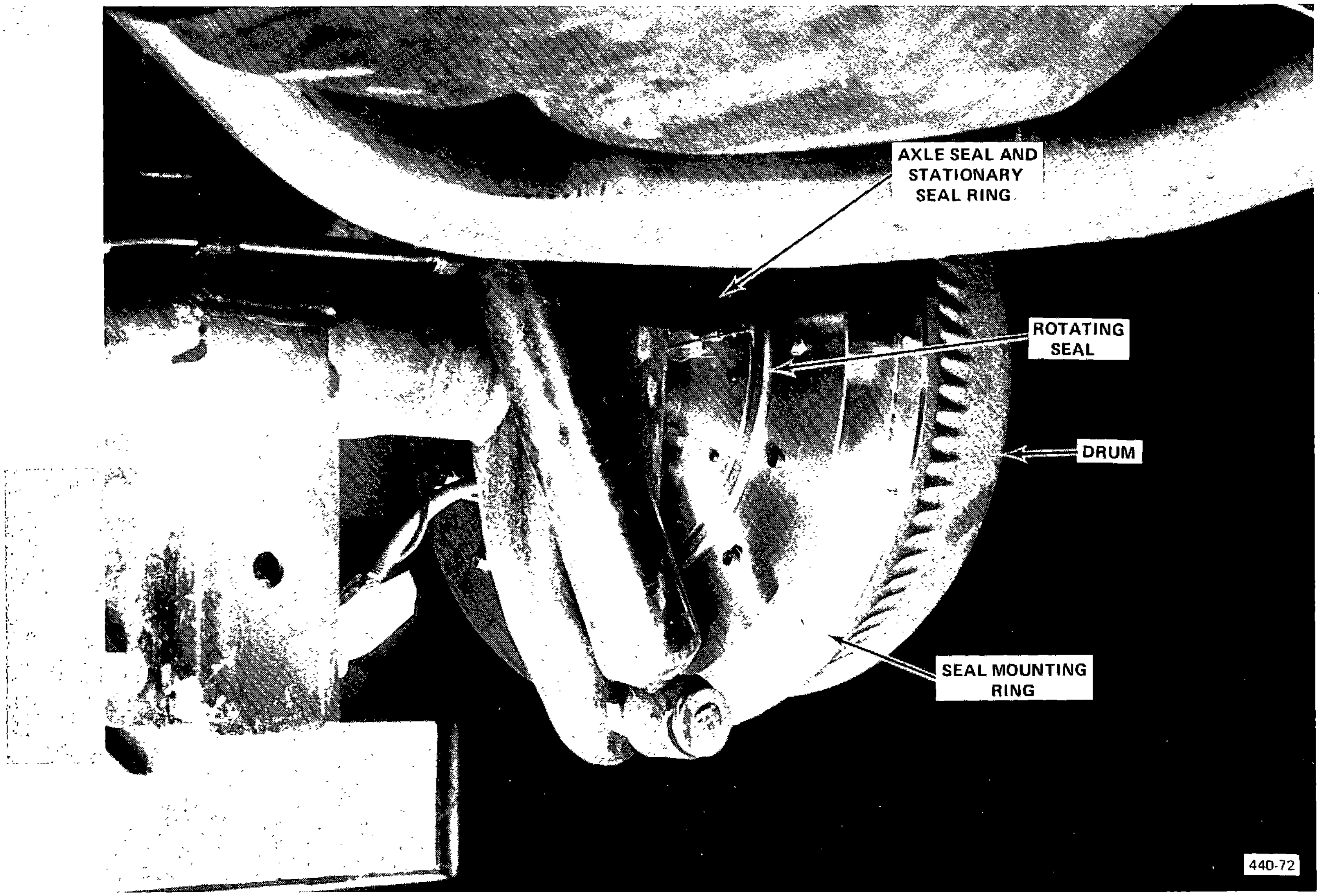


Figure 5-31 - Inboard View of Assembled Rear Drum Brake Emissions Collector

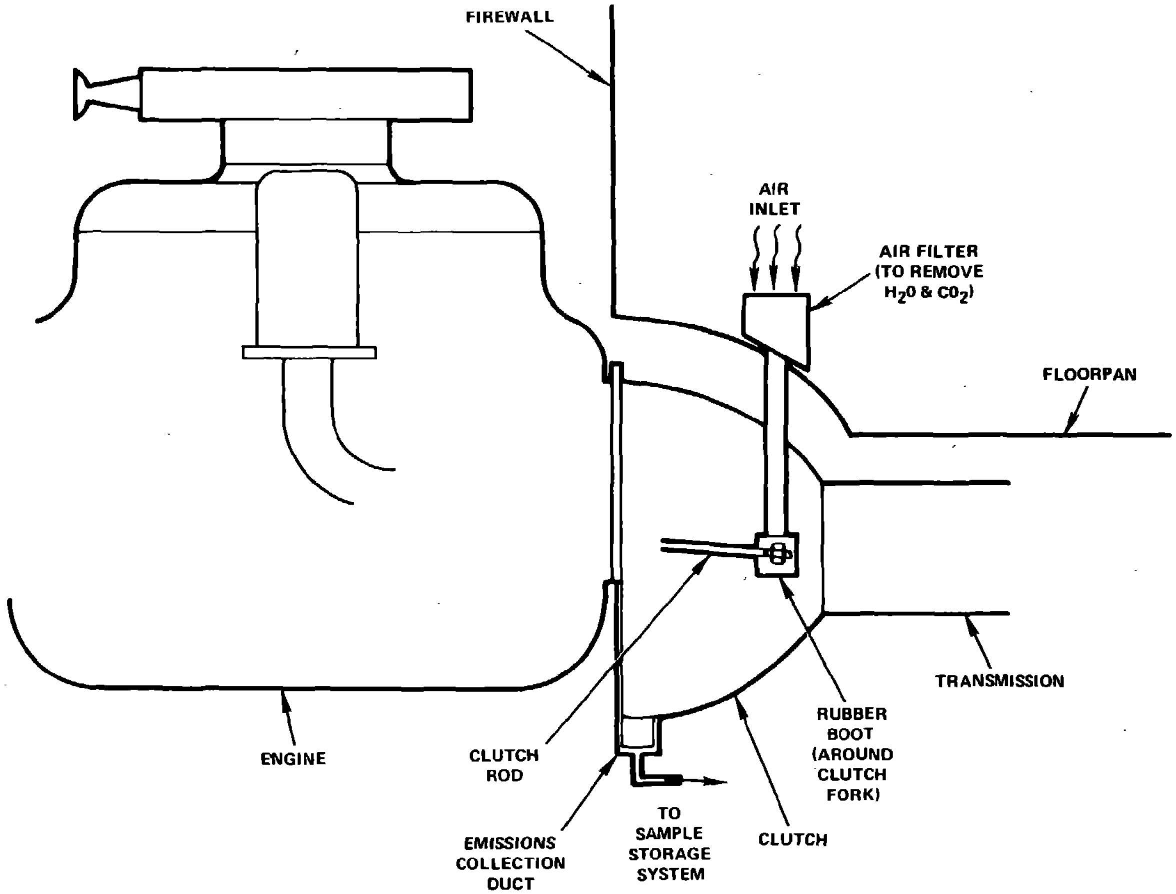


Figure 5-32 - Emission Collection System for Clutch

Figure 5-33 - General View of Covered Clutch

SECTION 6

INERTIA DYNAMOMETER TESTING OF THE DISC-BRAKE COLLECTOR SYSTEM

6.1 OBJECTIVES

There were three major objectives for the inertia dynamometer tests. First, it was necessary to demonstrate that a brake can be completely enclosed and not change in its mechanical operation. Second, it was necessary to demonstrate that the thermal response would not be seriously altered compared to the normal brake operation. Finally, the most critical unknown was the rotating seal operation.

6.1.1 Demonstration of Collection System Operation

The disc brake on the vehicle was designed to operate as a relatively open brake with a substantial air flow over its component parts. Shrouding of the caliper and rotor was a radical change from its original designed operating mode. The shrouded brake for emissions collection was a unique piece of hardware and thus it required testing on the inertia dynamometer, where modifications and adjustments could be made rapidly and rationally.

6.1.2 Thermal Response

It was known that shrouding would change the brake cooling. However, the effects of pulling air through the brake shroud even while the vehicle was stationary would negate some of the shielding effect of the shrouding. Thus it was necessary to determine the thermal response of the shrouded brake compared with that of its original design and to ascertain the effects of any thermal differences.

6.1.3 Rotating Seal Durability

At the beginning of the program, it was believed that the rotating seal life would be the most critical problem. Several questions arose. Would the initial design be suitable? Was a good back-up design available? Would any rotating seal survive under the conditions of operation? Were the claims of the seal manufacturers accurate and reliable? Thus the most critical objective of the inertia dynamometer test was to demonstrate the operation of a suitable rotating seal and to demonstrate its durability.

6.2 DYNAMOMETER TEST RESULTS

6.2.1 Sealing Practices for Disc Brake Collector

Figure 5-14 shows the major portions of the front disc brake collector. The silicone rubber gaskets form the major portion of the seals between the joints of the metal shroud. Once assembled on the wheel assembly, there were many leaks around the small screws holding the shroud together. Other leaks appeared at the welds on the outboard shield and the fittings on the modified dust shield. The leaks around the welds were eliminated by returning the parts to the shop for additional welding. The other leaks were eliminated by the liberal use of cured-in-place silicone rubber (see Figures 5-15 and 5-16).

6.2.2 Thermal Response Results

The first testing performed was to determine the thermal response of the shrouded disc brake as compared with that of the unshrouded disc brake. The inertia dynamometer used was set up to simulate a load of 1200 lbs on the brake, which is approximately 25 percent of the vehicle test weight (Figure 6-1). Each stop was from 30 mph to 0 mph at 300 psi line pressure. Stops were made at the rate of one per minute. The tests were run in still air. Figure 6-2 is a plot of temperature versus time for a thermocouple located in the outer pad and a thermocouple mounted on the backing plate. The solid curves are for the regular or unshrouded system, while the dashed curves are for the shrouded system, with no air being pumped through the system. Figure 6-2 shows that the shrouded brake heats faster than the unshrouded brake which was to be expected.

Figure 6-3 is a plot of the data from a series of tests on the shrouded disc brake system for thermal response of the outer brake pad under various air flow conditions. The plot shows temperature versus total energy input to the brake. The lowest curve on the plot is for the unshrouded brake and the highest is for the shrouded brake with no air flow as previously shown in Figure 6-2. The two middle curves are for air flows of 64 and 110 standard cubic feet/hour. The results show that increasing the air flow above about 60 SCFH (i.e., doubling the flow) had little effect on the cooling of the brake. Thus 60 SCFH was chosen as the flow to be set in the test vehicle.

6.2.3 Rotating Seal Operation

The initial rotating seal design described in Section 5.5.2.1 did not provide a suitable seal. It was therefore replaced with the design described in Section 5.5.2.2. The following tests were performed with the second design.

Testing was done to determine rotating seal effectiveness. The method used to determine the seal leakage rate was to apply air pressure to the closed shroud at 3.5 psi and measure the time required for the primary pressure regulator reading to drop from 1500 psi to 500 psi while the tank valve was closed. The total flow through the secondary regulator, set at 3.5 psi, was about 137 cc during this time. Figure 6-4 shows a plot of the leakage times versus wheel speed for a new seal, both lubricated and unlubricated. As can be seen, the leakage time increases as speed increases for both lubricated and unlubricated seals. Since the

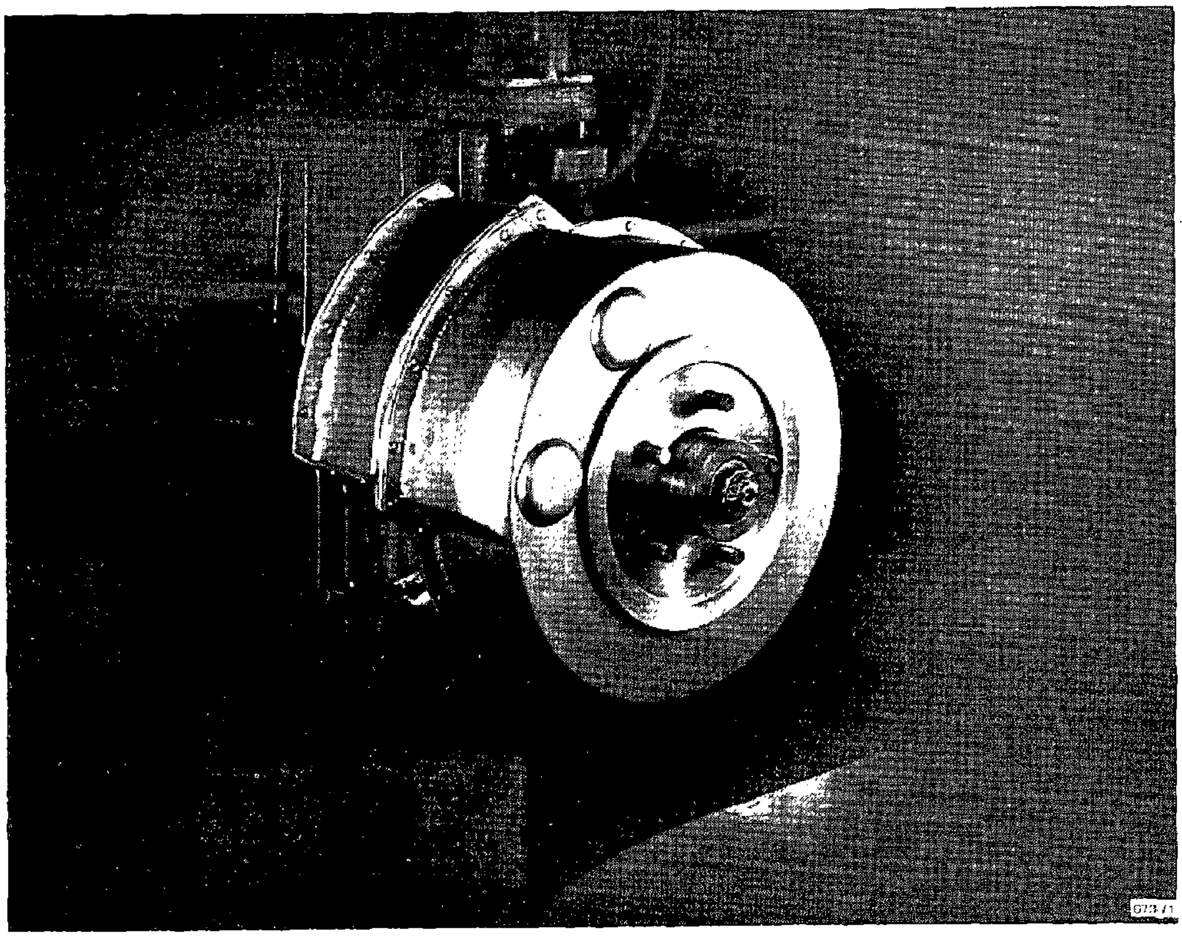


Figure 6-1 - Disc Brake and Emissions Collector Assembly Installed on Dynamometer

lubricated seal had lower leakage rates, the vehicle tests were all run with lubricated seals. This leakage test method was used throughout vehicle testing and seals were changed whenever the leakage rate fell below 20 seconds on a cold system.

One seal was then tested for a total of seven hours at 50 mph and the results of the leakage tests versus speed are shown in Figure 6-5. The seal was removed after testing and inspected. Figure 6-6(a) shows that most of the seal experienced little wear during the test. However, one section, approximately one inch long, showed abnormally high wear to a point of imminent failure (Figure 6-6(b)). This was apparently caused by spring distortion in this area causing higher pressure. Subsequent seals were inspected for this defect prior to assembly and this problem was avoided in all subsequent tests.

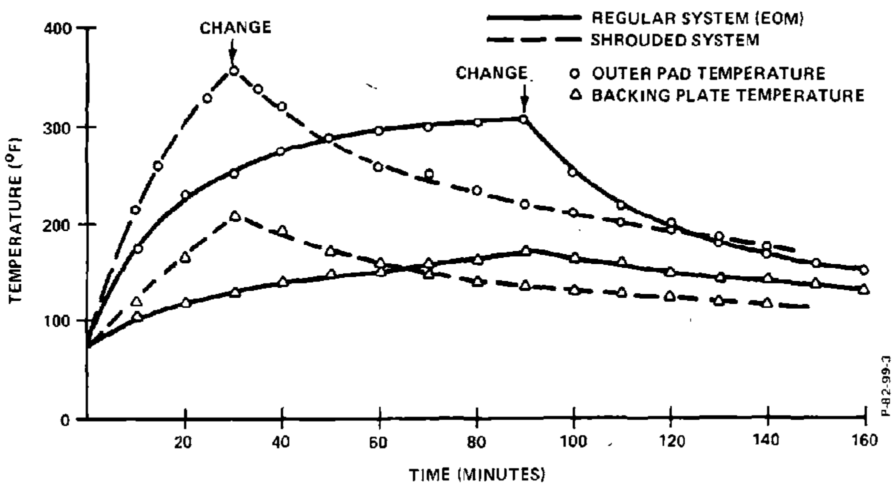


Figure 6-2 - Disc Brake Comparative Thermal Response Time (Static Air)

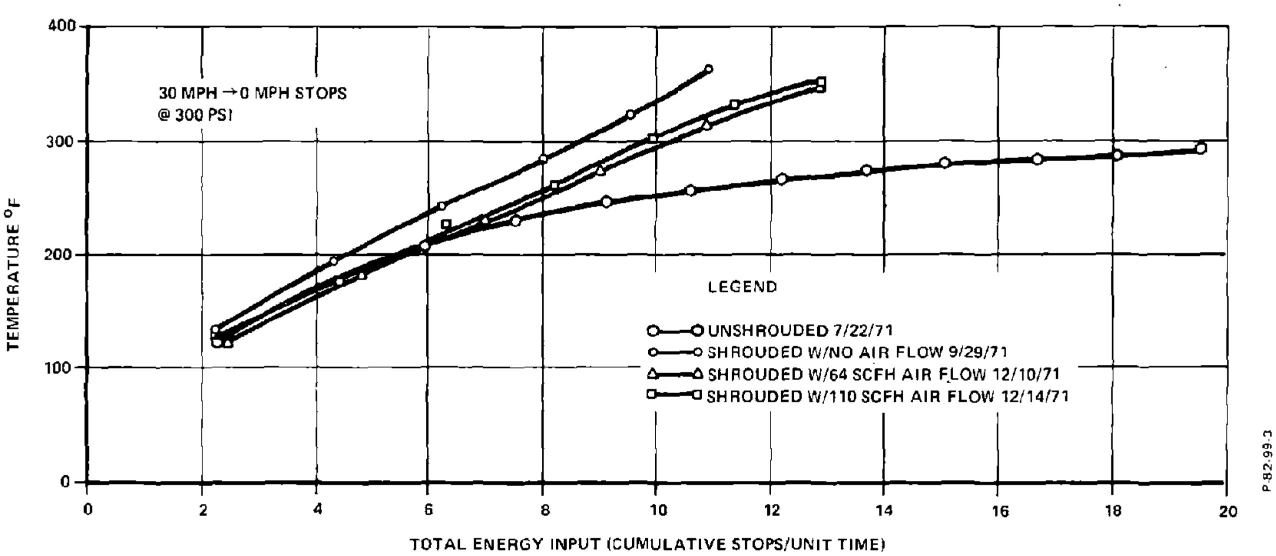


Figure 6-3 - Comparative Thermal Response Tests on a Disc Brake

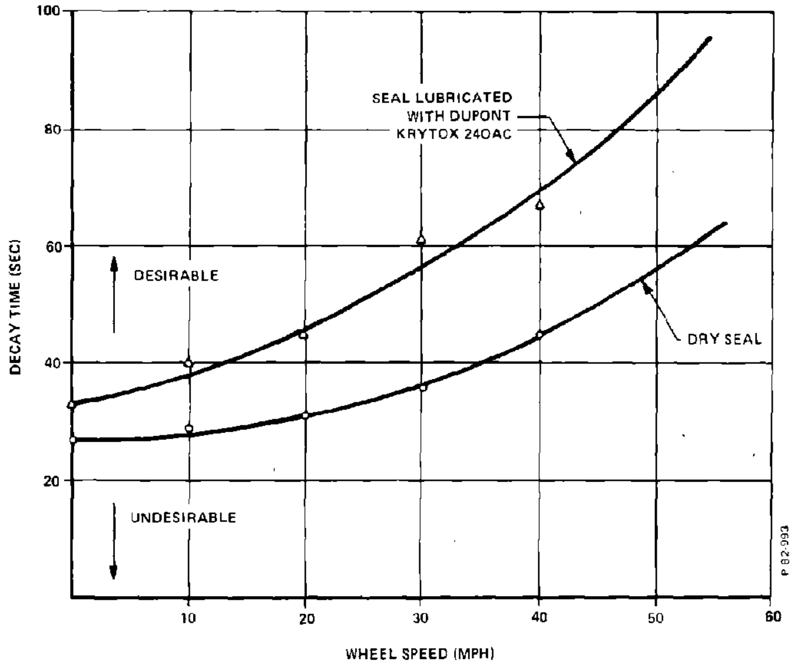


Figure 6-4 - Seal Leakage Versus Flow for Disc Brake Emissions Collector Showing Differences Between Dry and Lubricated Seals

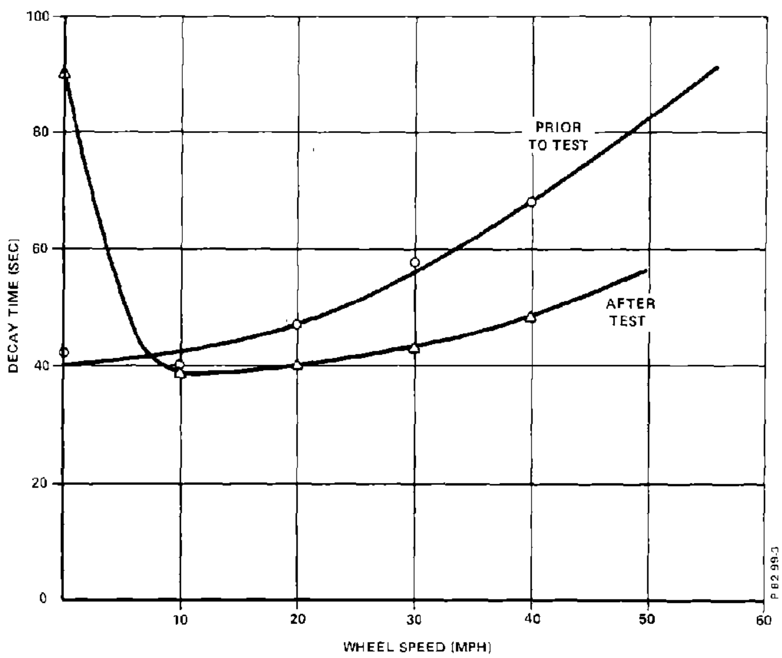


Figure 6-5 - Seal Leakage Rate Versus Speed Showing Differences Between New and Used Seal

(a) Normal Worn Seal

(b) Abnormal Wear to the Point of Imminent Seal Failure

Figure 6-6 - Seals From Disc Brake Emissions Collector Showing Normal and Abnormal Wear

A new rotating seal was installed at the beginning of the tests described in the next section. The initial seal integrity was equivalent to that of the seal used during the durability test runs. Figure 6-7 shows the data for this seal. The seal integrity was found to improve as the seal wore in. Moreover, the leakage rate further decreased as the wheel speed increased. Finally, the data for this seal agreed with all the trends shown by the earlier seals.

6.2.4 Emission Collections

A series of dynamometer tests were made to check out the operation of the entire disc brake emissions collection system. Identifying the tests by a year-month-day date code, a total of three tests were run:

Test 11222: Baseline

Test 20105: Baseline repeat

Test 20108: Baseline plus spray

Test 20108 was similar to the other two tests except that a mixture of 5 percent sodium chloride and 5 percent barium sulphate in water was periodically sprayed at the emissions collector. The salt and barytes (50 percent through 200 mesh and 50 percent through 325 mesh) were used to simulate a fall-winter slushy-wet road condition. Barium sulfate was used in place of sand so that the barium could be used as a tracer along with the chlorine in subsequent X-ray fluorescence analyses if needed.

Each of the tests was run for two hours on the inertia dynamometer. Pre-run and post-run time added to the total. During the two-hour run, 40 brake stops were made from 30 mph at 8ft/sec^2 deceleration rate (considered a normal stop). The wheel was run at 30 mph between stops. The temperature-versus-time plots for both the backing plate and the outer brake pads are shown in Figure 6-8. The reproducibility of Tests 11222 and 20105 was good. As expected, Test 20108 ran cooler because of the cooling spray.

Table 6-1 summarizes the dynamometer test results for flow rates, temperature control, and particulates collected. A slight decrease in carrier gas flow rate was seen as the filter picked up wear debris; this agreed with previous laboratory test data of pressure drop versus flow rates for Nuclepore membranes. The temperatures of the transfer line and filter assembly were held at 200 $\pm$ 20°F, the target temperature range, for the two base-line tests. The transfer-line temperature for Test 20108 fell below this for a brief period because of cooling effect of the spray. However, this was not considered a problem.

The particulates data are also given in Table 6-1. The wear debris on the filter was representative of normal vehicular brake wear debris found in drum brakes and trapped from previous Bendix sample

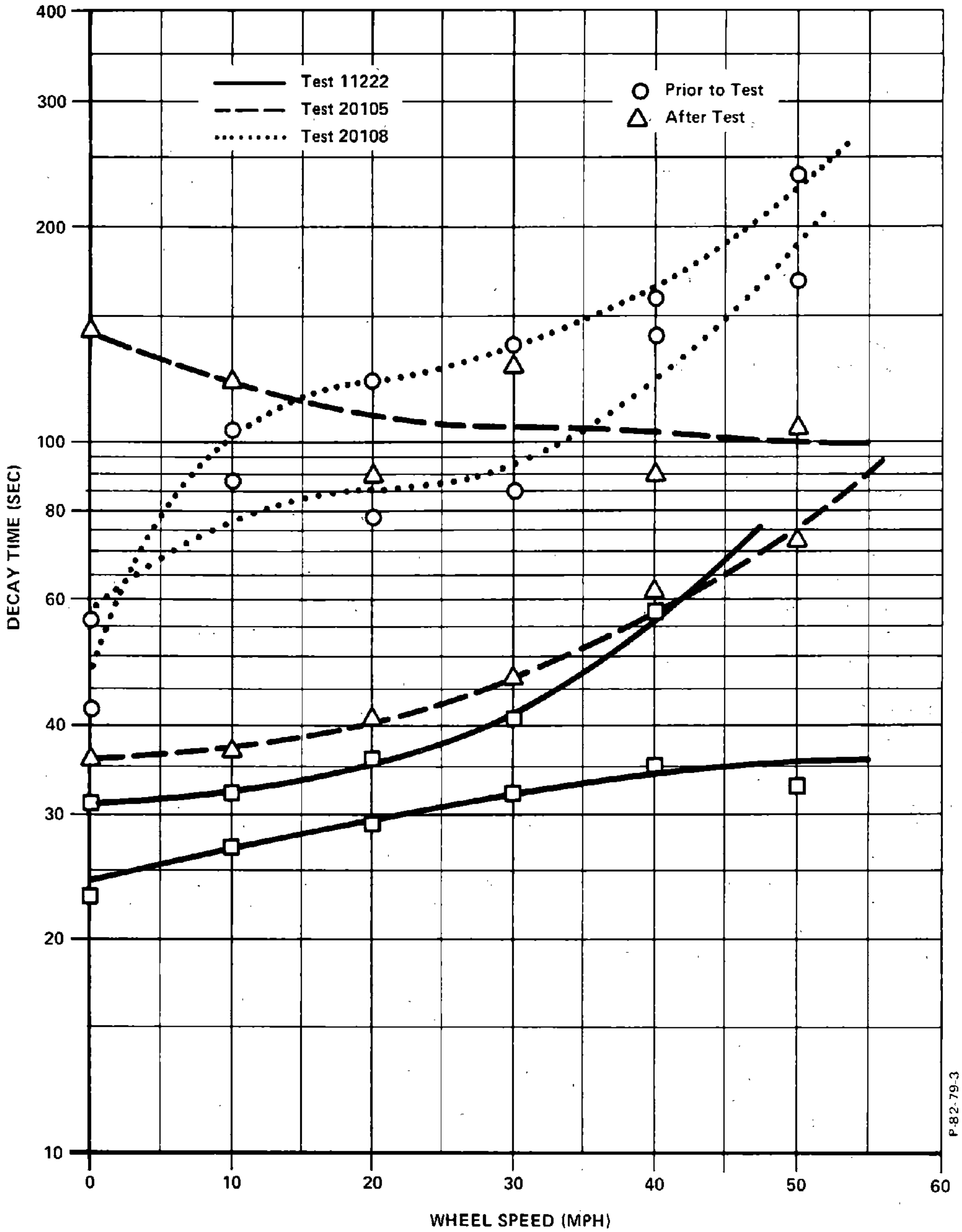


Figure 6-7 - Rotating Seal Leakage Rate Versus Wheel Speed
for Disc Brake Emissions Collector

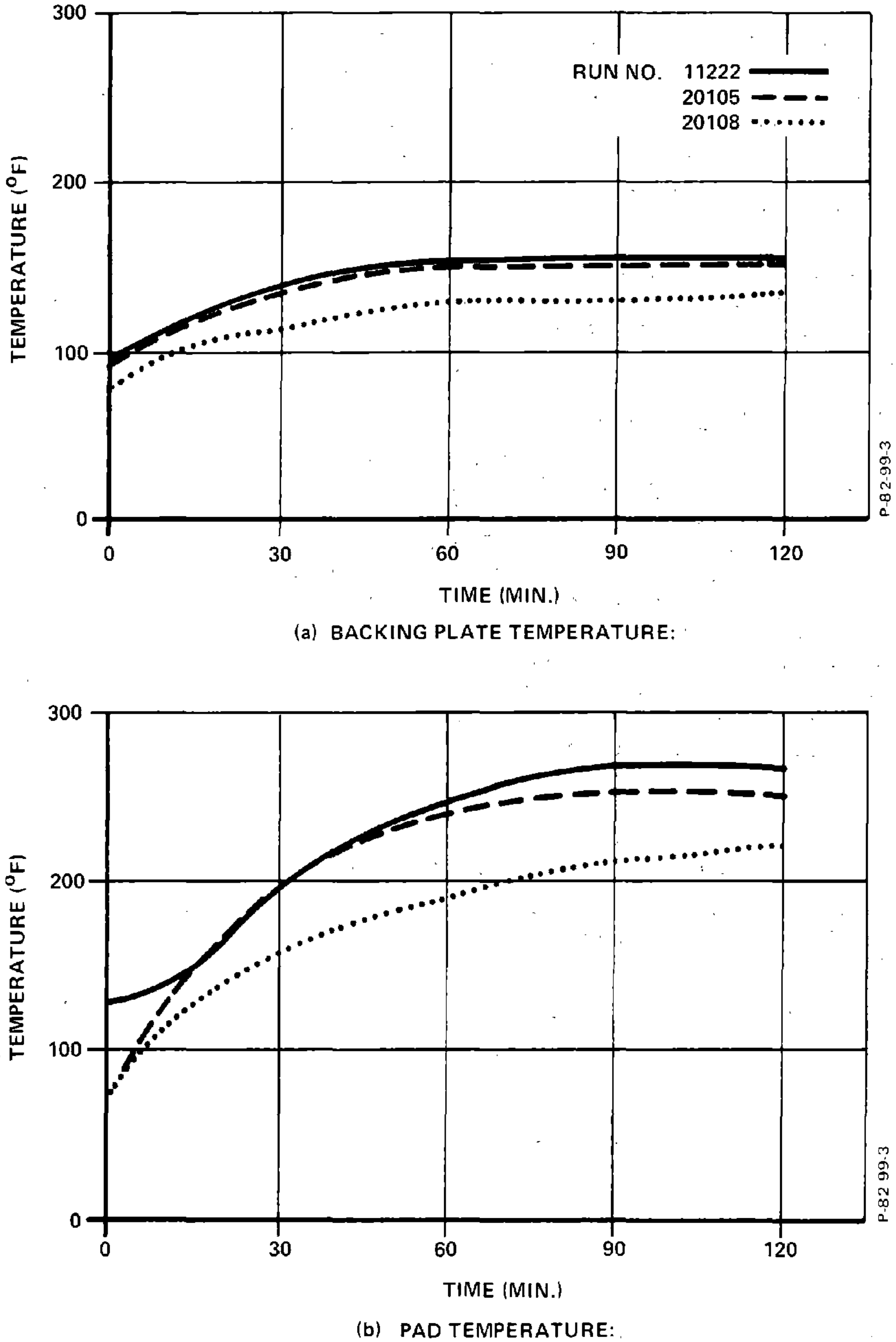


Figure 6-8 - Disc Brake Emission Collector Temperature dynamometer tests. The shroud samples contained mainly grease and some Teflon-graphite wear particles from the rotating seal. The amount of grease required was not known at the start of these tests. A liberal amount was used initially. Due to the heat of the rotating seal and to the air flow through the rotating seal (slight vacuum in the shroud), the grease flowed into the shroud and coated a portion of the inside surface near the rotating seal. This grease film attracted and held the wear debris. Assuming that the brake lining wear debris fraction* of the shroud sample is a constant (∿10 weight percent), the total particulates produced for each of the three tests agreed very well. The mean was 17.4 ± 0.3 mg. The air-borne fractions collected on the filters showed a wider variation with a mean of 12.8 ± 0.5 mg.

6.2.5 System Integrity

The third test in the preceding section was carried out to ascertain system integrity under simulated harsh road conditions. This test was run in same manner as the first two tests except that a mixture of 5-percent sodium chloride and 5-percent barium sulphate in water was sprayed at the emissions collector system. A total of two liters of this mixture, used to simulate fall-winter slush conditions, was sprayed on the system during the test. No traces of salt or of barium sulphate were observable on the inside of the collection system after testing. The temperature data for the heated transfer line and particulate filters and the particulate collection results for these tests are shown in Table 6-1. These results show that no salt entered the shroud system, and prove the integrity of the system used in vehicle testing.

Table 6-1 - Summary of Dynamometer Test Results

RUN NUMBER	CARRIER AIR FLOW (SCFH)		TEMPERATURES (°F)		PARTICULATES COLLECTED (mg)				REMARKS
	Initial	Final	Transfer Line	Filters	8 μ Filter	0.2 μ Filter	Shroud*	Total**	
11222	36	31	190-210	180-205	10.6	1.7	48.4	17.1	Baseline
20105	36	25	180-190	190-220	9.6	3.6	41.8	17.4	Baseline repeat
20108	36	26	170-220	190-215	10.2	2.7	46.6	17.6	Salt spray used; none detected inside collector

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*Includes grease and Teflon-graphite wear particles from seal (probably >90% of amount shown)
**Includes 10% of shroud figure

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*No assumption as to the actual content of wear debris in the samples taken from the brakes during the vehicle tests was necessary. Much less grease was used and practically none of it entered the shroud during these tests.

SECTION 7

VEHICLE TEST SCHEDULES

7.1 RATIONALE

7.1.1 Brakes

For a given vehicle brake system, friction material wear is primarily a function of the duty cycle. For light duty cycles, where pad and lining temperatures remain under 350°F, low wear results and is primarily due to the abrasive and adhesive wear mechanisms. Heavier duty cycles at higher temperatures give some combination of thermal, abrasive and adhesive wear. Under severe heavy duty where the use borders on abusiveness brake fade may occur. The inability of the brakes to hold the friction level results in part from the formation of gases (and wear debris) at the interface.

The amounts and types of gaseous and particulate emissions, as a function of brake duty, are not known. Moreover, as brake linings age, changes such as "hardening" occur, possibly with changes in the wear properties. Also, until disturbed, portions of the particulate emissions are known to be retained inside certain areas of the foundation brakes. Consequently, it is necessary to select a vehicle test program which will provide some combination of normal and heavy duty service.

7.1.2 Clutches

For a given vehicle, the friction material wear in the clutch is primarily a function of the duty performed. However, in most clutch applications, the energy absorption and temperature rise are usually less than in normal brake operation. Thus the wear and emission rates in clutches were expected to be very low.

7.2 TYPICAL TEST CYCLES

Several acceptable vehicle test cycles have been established and used by friction materials and brake system manufacturers. These are varied according to life and performance requirements, and for various stages of friction material conditions. The following test cycles appeared to be suitable for this program.

7.2.1 Burnish

A portion of the SAE Recommended Practice: Brake System Road Test Code - Passenger Car (SAE J843a) is called the Burnish. This test cycle is always used when the brakes are relatively new and thus is a part of the break-in procedure for new brakes. The test requirements are:

Stop speed:	40-0 mph
Stop deceleration:	12 fpsps
Stop interval:	As required to achieve 250°F initial brake temperature in a maximum of one mile.
Cooling speed:	40 mph (moderate acceleration to cooling speed).
Stops required:	200.
Optional:	Inspect and/or adjust brakes after burnish cycle.

7.2.2 Baseline

Since there was no cycle in SAE J843b comparable to a repeated, low duty-type baseline test, it was found necessary to adapt a portion of some other longer test cycle. This test would be used to serve as a reference for wear rate and brake emissions after other low and heavy duty test cycles. The baseline test selected was three days (12 circuits) of the Detroit Traffic Test schedule described below.

7.2.3 Detroit Traffic Test

The Detroit Traffic Test is used primarily to evaluate friction, life, and noise of commercial brake products. The normal operating range for passenger car brakes in the test is 180 to 280°F. This condition constitutes what a brake engineer calls a low-temperature wear test, but is actually somewhat more severe than for most driving. Testing is intentionally accelerated to reduce test costs, consequently the test tends to be more severe than average driving.

Table 7-1 describes the detroit Traffic Test route as modified for this program. The basic downtown circuit remains the same; only the starting and finishing routes are slightly altered. Each circuit begins with elevated brake temperatures. The vehicle merges and flows with the traffic during the prevailing traffic conditions. The following variations occur:

Stop speeds:	Variable: 45-0 mph maximum.
Snubs*:	Variable: 45 mph maximum.
Stop deceleration:	Variable: 20 fpsps maximum.
Stop interval:	As required to maintain flow in traffic.

*Decelerations to lower speeds, but not stops.

Table 7-1 - Detroit Traffic Test Route (Modified)

A. Drive from Bendix Research Laboratories (BRL) to 12-Mile Road and Woodward Avenue via the following route:

Left on Civic Center Drive to Greenfield Avenue

Left on Greenfield Avenue to 12-mile Road

Right on 12-Mile Road to Woodward Avenue

Turn right on Woodward Avenue and park on Service Drive to check instrumentation.

B. Detroit Traffic Route:

Starting on Woodward Avenue (just South of 12-Mile Road), drive south to Adams Avenue (starting point of downtown loop).

Right on Adams Avenue (West) to Park Avenue

Left on Park Avenue to Bagley Avenue

Right on Bagley Avenue to Third Avenue

Left on Third Avenue across Michigan Avenue to Fort Street

Left on Fort Street to Griswold Street

Right on Griswold Street to Jefferson Avenue

West on Jefferson Avenue to Washington Boulevard

Right on Washington Boulevard to Fort Street

Right on Fort Street to Cadillac Square

Right on Cadillac Square to Randolph Street

Left on Randolph Street to East Fort Street

Right on East Fort to Brush Street

Left on Brush Street to Macomb Street

Left on Macomb Street to Randolph Street

Cross Randolph Street to Broadway Avenue

Right on Broadway to Witherell Street

Right on Witherell Street to Adams Avenue

Left on Adams Avenue to Woodward Avenue

This completes one downtown loop. Complete a second downtown loop by continuing west to Park Avenue and following around and returning to the corner of Adams and Woodward Avenues

After the Second downtown loop, turn right and follow Woodward Avenue (north) to 12-mile Road

Turn left, making U-turn around center island and return south on Woodward Avenue, crossing 12-Mile to park on Service Drive again to recheck instrumentation

This completes one circuit of the Detroit Traffic Test.

C. Return to BRL from 12-Mile Road and Woodward Avenue by following route:

After checking out instrumentation, drive west on 12-Mile Road to Greenfield Avenue

Left on Greenfield Avenue to Civic Center Drive

Right on Civic Center Drive to BRL

D. Estimated time scheduling:

Time	ΔT (min)	
8:00 - 8:15	15	Vehicle preparation
8:15 - 8:30	15	BRL to 12-Mile and Woodward
8:30 - 10:15	105	First circuit
10:15 - 12:00	105	Second circuit
12:00 - 12:45		Lunch
12:45 - 2:30	105	Third circuit
2:30 - 4:15	105	Fourth circuit
4:15 - 4:30	15	Return to BRL
4:30 - 4:45	15	Prepare vehicle for overnight layover

E. Estimated Miles:

BRL to route and return	12
Each circuit 26.5 x 4	106
	118 miles/8-hour shift.

Estimated total miles: 12 x 118 = 1416 miles.

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Cooling speed: Normal traffic speeds.

Stops required: As required in flow of traffic.

The duration of the Detroit Traffic Test is not fixed for normal original equipment manufacturers' testing. For the purposes of this program, a 12-day test duration was chosen. Each day of testing was expected to provide approximately 118 test miles which, in turn, was expected to yield a total of approximately 1416 test miles.

7.2.4 10-Stop Fade and Recovery

A portion of SAE J843a is called the fade sequence. This test cycle is used as the first high-temperature operation of a friction material. The test is used to simulate a vehicle making repeated heavy-duty stops. The fade sequence is usually followed by a recovery sequence. The test requirements are:

Fade:

Initial brake temperature:	150°F before first stop.
Stops required:	10.
Stop speed:	60-0 mph.
Stop deceleration:	15 fpsps (in normal driving gear).
Stop interval:	0.4 mile.
Cooling speed:	60 mph (accelerate at maximum speed).

Recovery:

Cooling speed:	40 mph.
Cooling interval:	1.0 mile.
Stops required:	12.
Stop speed:	30-0 mph.
Stop deceleration:	10 fpsps.

Lining temperatures are recorded before each fade stop and before each recovery stop.

7.2.5 15-Stop Fade and Recovery

The 15-Stop Fade and Recovery is comparable to the 10-Stop Fade and Recovery described earlier, except that an additional 5 stops are made when the brakes are already very hot.

7.2.6 Reburnish

The Reburnish portion of SAE J843a is essentially similar to the Burnish portion except that only 35 stops are required.

7.3 SELECTED VEHICLE DRIVING SCHEDULE

Although there are many acceptable original equipment manufacturers' friction material tests to measure a specific condition or combination of conditions, there is no one test which adequately matches normal driving conditions which would be representative of all vehicles. Consequently, it became necessary to devise a rational and meaningful vehicle test driving schedule.

Table 7-2 lists the selected vehicle driving schedule for each vehicle test configuration used in the program. A total of seven test schedules was chosen and each was followed by a measurements procedure (take emissions samples, measure wear, inspect systems, and replace worn parts). The first three tests -- Burnish, After-Burnish Baseline, and Detroit Traffic -- represent the low-temperature tests. The final four tests -- 10-Stop Fade, After-Fade Baseline, 15-Stop Fade, and Final Baseline -- represent the high-temperature tests.

7.3.1 Burnish

The initial test is the Burnish. The original equipment and aftermarket linings mate and conform to the initial condition of the rotor whether it is in its original configuration, as-used condition after vehicle test 1, or its turned condition prior to vehicle test 3. It was anticipated that the emissions would be different than those for worn-in linings.

7.3.2 After-Burnish (A.B.) Baseline

The second test is After-Burnish (A.B.) Baseline. This three days of Detroit Traffic Test was run at this time so that the other Baselines run at the later times could be compared to the A.B. Baseline for the amount and type of emissions.

7.3.3 Detroit Traffic Test

The third and longest test employed was the 12-day Detroit Traffic Test. This test represents the low-temperature-wear or normal-duty-wear tests. The results of this test could also be compared to the A.B. Baseline Test.

The end of the Detroit Traffic Test was the end of the low-temperature-wear testing.

7.3.4 10-Stop Fade and Recovery

The 10-Stop Fade and Recovery was the fourth test sequence and the start of the heavy-duty or high-temperature testing. During this test, the front brakes experienced temperatures above 500°F, while the rear brakes experienced temperatures above 350°F. The combination of increased temperature and increased duty was expected to change the amount and type of wear debris generated, as compared to the previous low-duty tests.

Table 7-2 - Vehicle Test Schedule

Test	Estimated Time (Days)	Total Time (Days)	Estimated Lining Loss (Mils)	Purpose
Burnish Measurements*	2.0 1.5	3.5	5	Lining Preparation
After Burnish (A.B.) Baseline Measurements	3.0 - 1.5	4.5	5	Base Line Data
Detroit Traffic (Modified) Measurements	12.0 1.5	13.5	10	Low Temperature Wear
10-Stop Fade and Recovery Reburnish Measurements	1.5 1.0 1.5	4.0	10	High Temperature Wear
After Fade (A.F.) Baseline Measurements	3.0 - 1.5	4.5	5	Base Line Data
15-Stop Fade and Recovery Reburnish Measurements	1.0 1.0 1.5	3.5	10	Abusive Wear
Final Baseline Measurements	3.0 - 1.5	4.5	5	Base Line Data
		38.0		

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*Take emissions samples, measure wear, inspect systems, and replace worn parts.

The Fade and Recovery were then followed by the Reburnish sequence.

7.3.5 After-Fade (A.F.) Baseline

This fifth test sequence was identical to the second and seventh test sequences (and similar to the third), but only the conditions of the friction materials had changed. This test was expected to determine the permanent changes in the amount and type of wear debris generated for friction materials taken through high-temperature and heavy-duty stops.

7.3.6 15-Stop Fade and Recovery

The sixth test sequence was the 15-Stop Fade (and Recovery) in which the friction materials were taken to even higher temperatures than for the 10-Stop Fade. The five additional stops performed after the brakes were already hot produced temperatures above 575°F. This is abusive braking, and rarely occurs. The emissions generated were expected to be different again, as compared with the low-duty tests and the 10-Stop Fade.

The Fade and Recovery were then followed by the Reburnish sequence.

7.3.7 Final Baseline

The results of this seventh and last test sequence can be compared with the results of the identical second and fifth test sequences. This test concluded the determination of the effects that high-temperature and heavy-duty tests have on brake emissions.

SECTION 8

SAMPLING AND ANALYTICAL PROCEDURES

8.1 RATIONALE BASED ON COLLECTOR DESIGNS

8.1.1 Particulate Emissions Collection

During the braking process, particulate emissions are generated by the rubbing action of the friction materials and the rotors. The OEM brake configurations (left wheels of test vehicle) release emissions which reside in either of two areas depending on the brake type (Table 8-1). The disc brake releases much of the emissions to the atmosphere while a small amount remains in the brake. The drum brake releases a lesser amount to the atmosphere and retains sizeable portions on the drum rubbing surface and on the brake parts. The brake emissions collectors perform two functions not encountered in normal brake operation: collect all the debris generated and fractionate the debris. Table 8-2 summarizes the particulate emissions samples produced.

8.1.2 Gaseous Emissions Collection

During the braking process, gaseous emissions are also generated by the heat associated with the rubbing action of the friction materials and the rotors. The OEM brake configurations release gaseous emissions which again reside in either of two areas. Most of the gaseous emissions are released into the atmosphere; some of the high molecular weight materials distill from the hot surfaces and condense on the cooler brake parts. The emission transfer lines used in conjunction with the collectors therefore were heated so that almost all gaseous emissions could be transferred to the gas collection traps.

8.2 PARTICULATE EMISSIONS REMOVAL FROM COLLECTORS

8.2.1 Collection of Particulate Emissions

A detailed step-by-step sequence was prepared for the collection of brake and clutch emissions. This information is included as Appendix C. The weights of each sample collected are reported in Section 9 under Vehicle Test Results.

8.2.2 Disc Brake Samples

In all cases, three samples were obtained from the right front disc brake collector: sump sample (including debris in rivet holes, on lining surfaces, and inside caliper piston), wear debris which remains in the brake; surfaces sample (including all other debris remaining in the brake collector); and the airborne sample (debris collected on the

Table 8-1 - Comparison of Disc Brake Versus Drum Brake Operating Conditions

Parameter	Disc	Drum
Type of system	Open	Closed
Air flow	High	Low
Emissions	Relatively few trapped	Much trapped in surfaces and in sump
Third-body abrasive wear	Relatively none	Some

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Table 8-2 - Samples Produced by Brake Emissions Collection

Sample	Disc Brake	Drum Brake
Sump	Trapped debris* - includes that in rivet holes, on pads and in caliper piston	Trapped debris* - includes that in rivet holes, on linings, and on drum surface+ +Provides third-body wear
Surfaces	Accumulated on shroud - normally road dropout	Accumulated on brake surfaces*
Airborne	Airborne samples collected on filters	Airborne samples collected on filters

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*Normally not completely released during brake operation. (This may be a "controllable" material which could be disposed of properly).

8.0μ and 0.2μ Nuclepore filter train). The contract did not require Bendix Research Laboratories to sample the left front disc brake; however, some samples were taken so that it would be possible to assess the quantity of material remaining in an OEM configuration disc brake. These data were prepared for Section 9.

8.2.3 Drum Brake Samples

In all cases, three samples were obtained from the right rear drum brake collector: sump sample (including debris in rivet holes, on lining surfaces, and on drum rubbing surface), wear debris which remains in the brake; surfaces sample (including all other debris remaining in the brake collector and on the brake surfaces); and the airborne sample (debris collected on 8.0μ and 0.2μ Nuclepore filter train). The contract required that selected left rear drum brake samples be taken in order to assess the quantity of material remaining in an OEM configuration drum brake. These data were prepared for Section 9.

8.2.4 Clutch Samples

Since the airborne samples taken from the clutch for vehicle test 1 were extremely small compared to the corresponding airborne samples from the brakes, it was decided to accumulate the entire sump and surfaces samples for all three vehicle tests. These data were prepared for Section 9.

8.2.5 Improved Friction Material Weighing Procedure

The original equipment drum brake linings and disc brake pads were riveted to their corresponding brake shoes. The weight of the metallic shoe placed the combined weights in excess of 400 gm; the weight could then be recorded to the nearest 0.1 gm. The anticipated weight differences of approximately 0.5 gm would have had less than desired accuracy. By removing the rivets, the weights of the friction materials alone could be determined. Since all friction material weights were less than 200 gms in this condition, weighing on an analytical balance was possible. After the friction materials were dried in a vacuum oven at 90°C, the weights were recorded to the nearest 0.01 gm, giving the desired accuracy. The linings were then refastened to the shoes by flat head nuts and bolts for vehicle installation and testing.

8.3 ANALYTICAL PROBLEM DEFINITION

8.3.1 Composition of Wear Debris

The brake converts the kinetic energy of the moving vehicle into heat, absorbs the heat, and eventually dissipates it to the atmosphere. As a result of the energy conversion at the stator-rotor interface, the compositions and microstructures of the brake lining and rotor surfaces are altered.

At low service temperatures, the phenolic resin and organic friction modifiers in the friction material undergo ploughing and mechanical damage before they convert on the surface to compositions with slightly higher carbon/oxygen ratios. At somewhat higher use temperatures, the resin and organic friction modifiers convert to carbon more readily, and this in turn oxidizes to carbon dioxide. At the same time, the asbestos, converted asbestos, and other converted materials wear away more rapidly because of the reduced binder strength and volume at the surface. At still higher temperatures, the asbestos converts from its fibrous form to an olivine powder having little or no reinforcing value. When heat is generated at the sliding interface much faster than it can be dissipated, the temperature rises and reaches a point where the lining or pad components decompose, oxidize, or melt. The region near the sliding surface of the lining containing these reacted components is called the frictional heat affected layer (FHAL).

At low service temperatures, the surface asperities of the rotor are mechanically worked and the surface becomes essentially free of graphite. Also, the cementite plates in the surface layer are broken up and distributed as fine particles in a ferrite matrix. When the surface is subjected to very high temperatures, martensite forms at the rubbing surface, with an accompanying increase in surface hardness.

Consequently, the thermal and mechanical forces which act at the friction couple interface produce a complex chemically and physically altered microstructure which cannot be accurately described for the resultant wear debris. Figure 8-1 shows the thermogravimetric analysis of typical rear drum brake wear debris. Table 8-3 gives an estimate of the chemical composition of wear debris.

8.3.2 Analytical Methods for Asbestos and Their Rationale

As pointed out earlier, asbestos is a complex inorganic material with the approximate composition formula:

$$Mg_3\ (SiO_5)\ (OH)_4 \text{ or } 3MgO \cdot 2SiO_2 \cdot 2H_2O$$

The basic unit has a fibril form. Asbestos is readily identified when alone or in simple mixtures at high concentrations by the following analytical methods:

X-Ray diffraction

Thermal methods

Microscopy

Infrared analysis

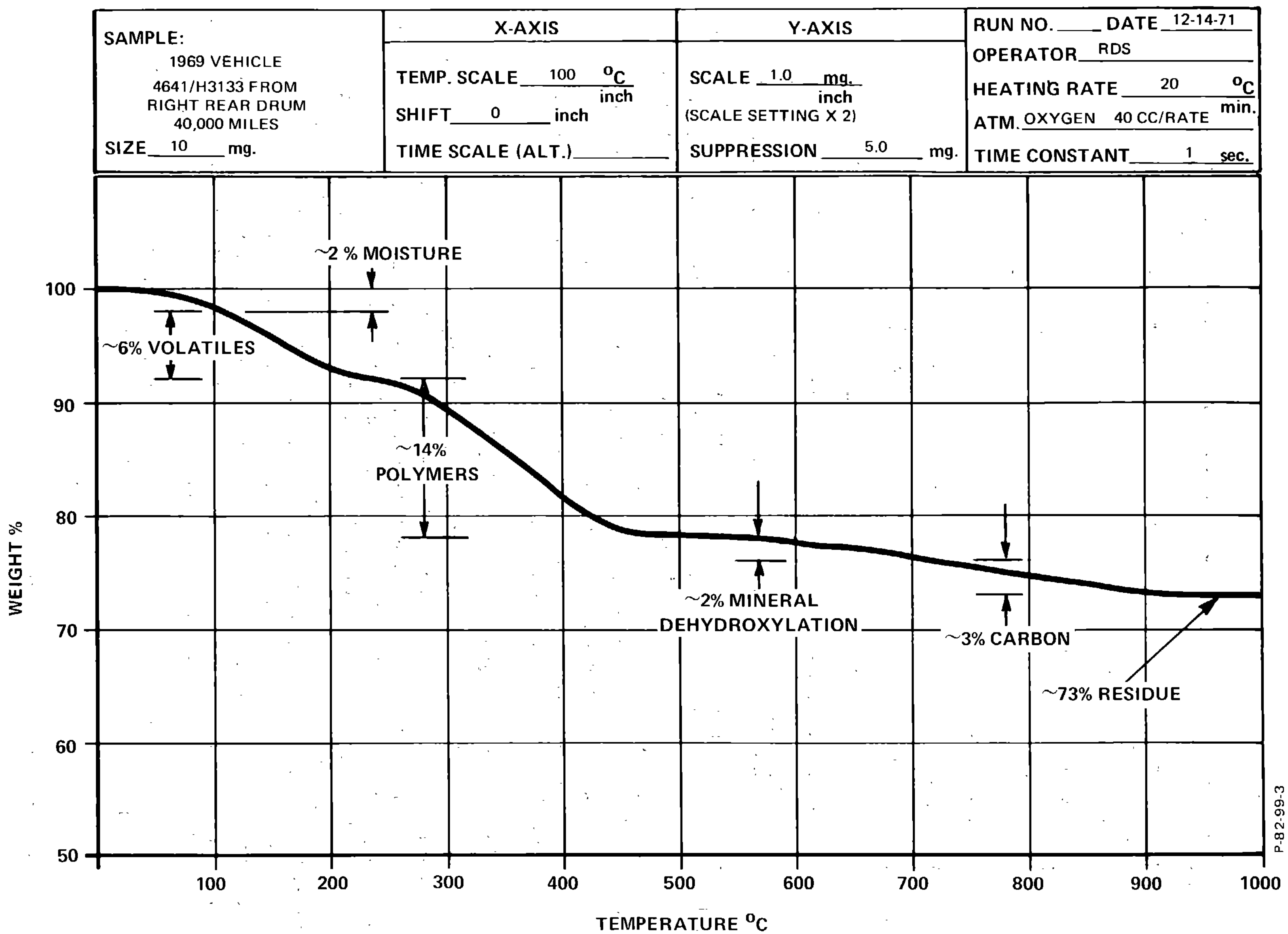

Figure 8-1 - Thermal Analysis of Wear Debris

Table 8-3 - Estimated Chemical Composition Characteristics of Wear Debris

Description	Percent	
Low Molecular Weight Degradation Products	2-10	
Polymeric Components	12-20	20-30
Carbonaceous Material	1-5	
Inorganics:		
Mineral	$\sim$10-30	
Olivine	$\sim$20-40	
Oxides (from Lining)	0-10	70-80
Fe_2O_3 (from Rotor)	5-15	
Asbestos	<1	

However, in complex mixtures, or at very low concentrations, the analysis for asbestos is very difficult. In brake wear debris, the problem is compounded because the reaction products of asbestos, forsterite and olivine, have similar elemental ratios and similar X-ray diffraction patterns. The only sensitive method which can be used is microscopy. In extremely low concentrations, asbestos is identifiable in the electron microscope by its physical shape (tubular fibril), which is distinguishable from that of other fibers and particles.

8.3.3 Microscopy Methods for Asbestos

At the beginning of this program, there were one optical and three electron microscopy methods for the determination of asbestos content. The optical microscopy method was established by the U.S. Public Health Service with the Asbestos Textile Industry[(8-1)*] to monitor ambient air quality for large asbestos fibers in areas of high concentration. In this method, an asbestos content with more than 90 percent fibers collected on a membrane filter was examined at 400 or 430 diameters magnification with phase contrast optics. The phase contrast rendered the background filter transparent and enhanced the viewing of the fibers. Only fibers greater than 0.5μ in diameter and 5.0μ in length were detected and reported. No fiber size degradation took place in this analysis.

Two electron microscopy methods (developed by Battelle Columbus Laboratories[(8-2)] and Mt. Sinai School of Medicine[(8-3)]) existed

*References appear at the end of this section.

at the start of the program while the third was just being introduced (University of California, School of Public Health[8-4]). These methods are compared in Table 8-4. The Battelle and Mt. Sinai methods are characterized by asbestos fiber size degradation to produce more fibrils. This size degradation was not desirable for this program, as one of the objectives was to ascertain the size distribution of the asbestos fibers in the brake emissions. On the other hand, the University of California method was desirable because of particle size preservation. However, the magnification range was found to be low, making it difficult to see the smaller asbestos fibers and fibrils found in brake wear debris.

8.4 BENDIX ANALYTICAL METHOD FOR ANALYSIS OF ASBESTOS IN BRAKE EMISSIONS

8.4.1 Criteria and Flow Chart

Three important criteria had to be met by the analytical method used: the very small portion of brake debris used had to be representative of the much larger sample collected; the analytical steps could not degrade the particle size distribution of the asbestos fibers obtained; and the results obtained must be indicative of the actual asbestos content of the sample. These criteria were met by the analytical scheme outlined in Figure 8-2.

8.4.2 Analysis of Brake Emissions

A detailed step-by-step sequence was prepared for the analysis of brake emissions. This information is included as Appendix D. The asbestos content of each sample analyzed is reported in Section 9 under Vehicle Test Results.

8.4.3 Representative Sampling and Low Temperature Ashing (LTA)

After desiccating the samples to remove adsorbed water and weighing for material balance purposes, two representative sampling procedures were used. In the first sampling, 10 fractions, each approximately 2 to 5 mg, were used to accumulate approximately 20 to 50 mg of wear debris (Figure 8-3). If the total sample weight was less than 100 mg, the entire sample was used. The large amount of carbonaceous material was responsible for the fluffy appearance of the wear debris. Figure 8-4 shows a scanning electron photomicrograph of a group of several fibers greater than 50 microns. Their ends were not visible and their exact length could only be obtained by LTA or by destroying the wear debris particle which, in turn, might have reduced fiber length. The LTA process is described in Figure 8-5.

Table 8-4 - Transmission Electron Microscopy Methods

	BATTELLE	MT. SINAI	U OF CALIFORNIA
Magnification	40,000X	42,000X	3,000X
Size Degradation	Yes	Partial	No
Size Distribution	Changed Completely	Changed Slightly	Unchanged
Concentration Used	Yes	No	No
Minimum Detectable Limit	∿0.000001%		0.01%
Size Detection (μ)			
Minimum	0.03 X 0.09	0.03 X 0.09	0.05 X 1.5
Maximum	0.20 X 10	0.20 X 10	0.50 X 40
Statistics	20 Grid Openings (∿100 Fibrils)	6 Grids X 2 Openings/Grid (∿10-100 Fibrils)	Not Known
Customer	EPA	Asbestos Workers Union	Asbestos Workers Union

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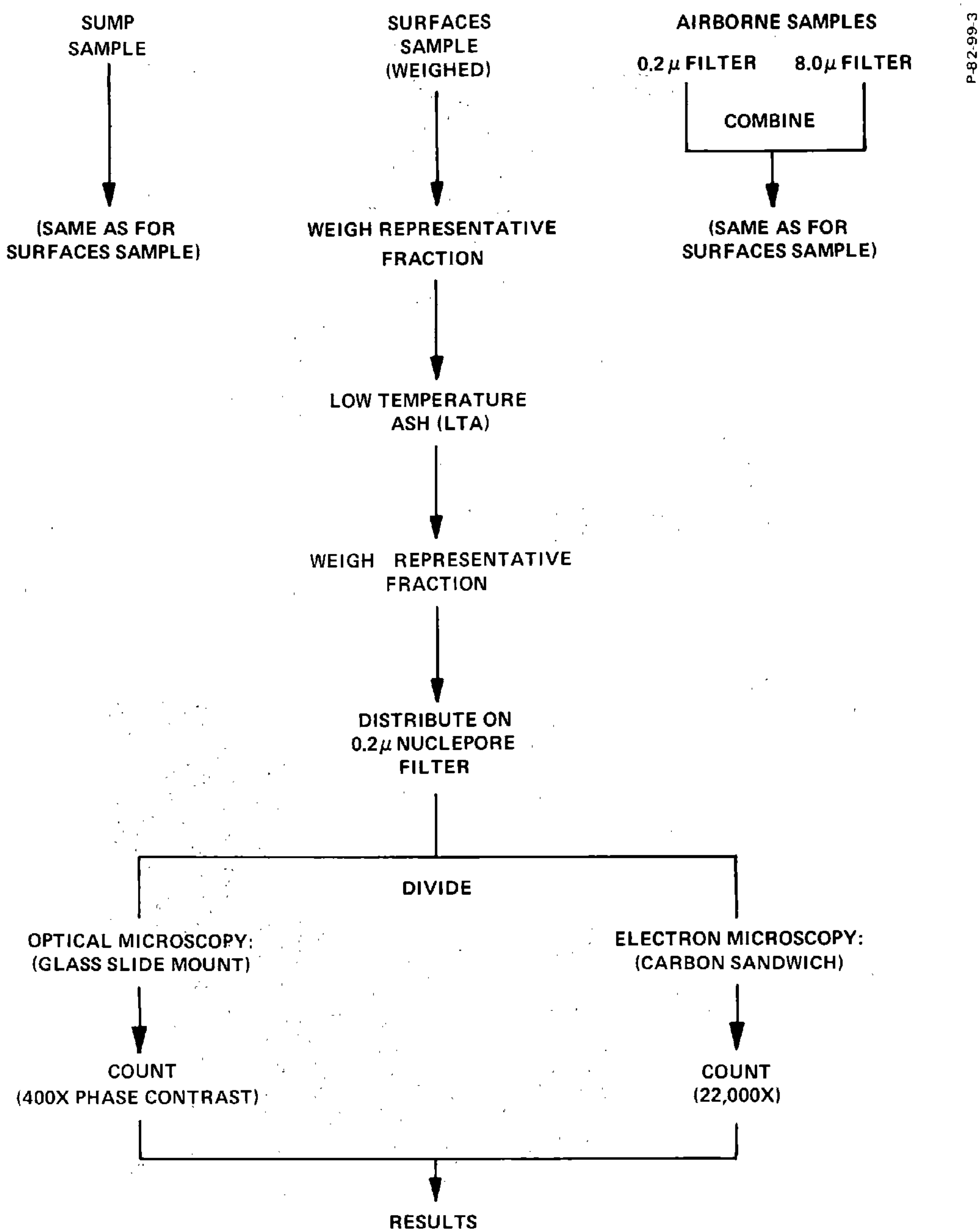


Figure 8-2 - Flow Chart for Particulates Analyses

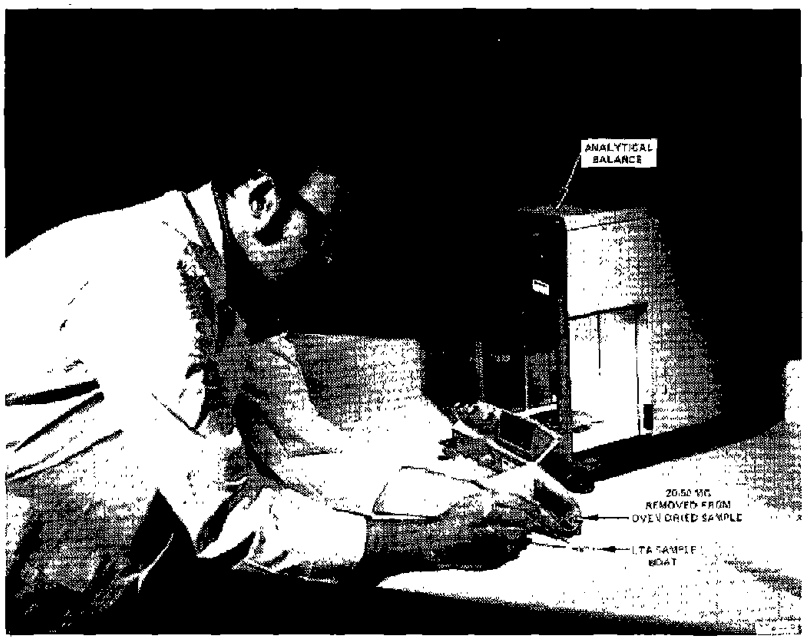


Figure 8-3 - Representative Sampling for Analysis

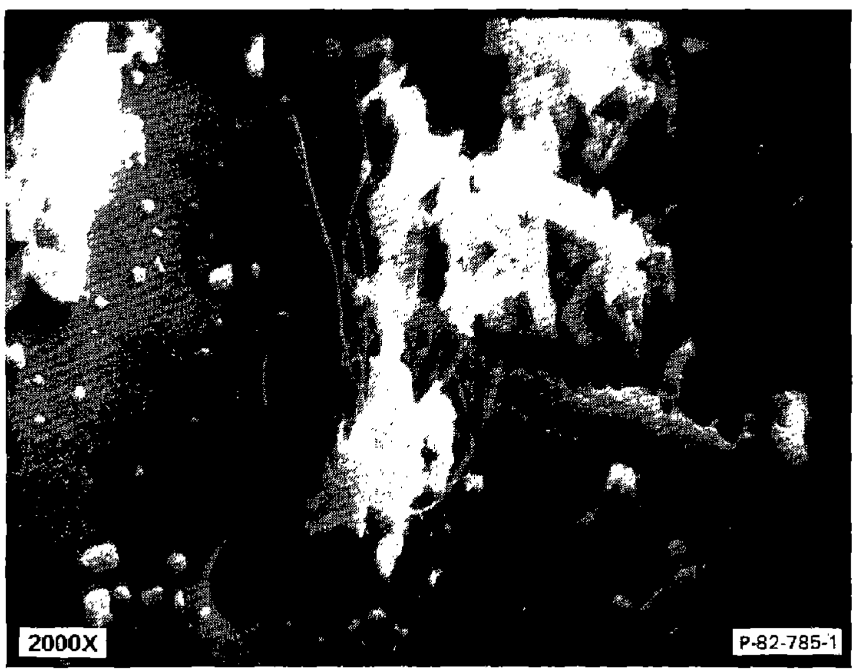


Figure 8-4 - Wear Debris Collected on 8μ Nuclepore Filter

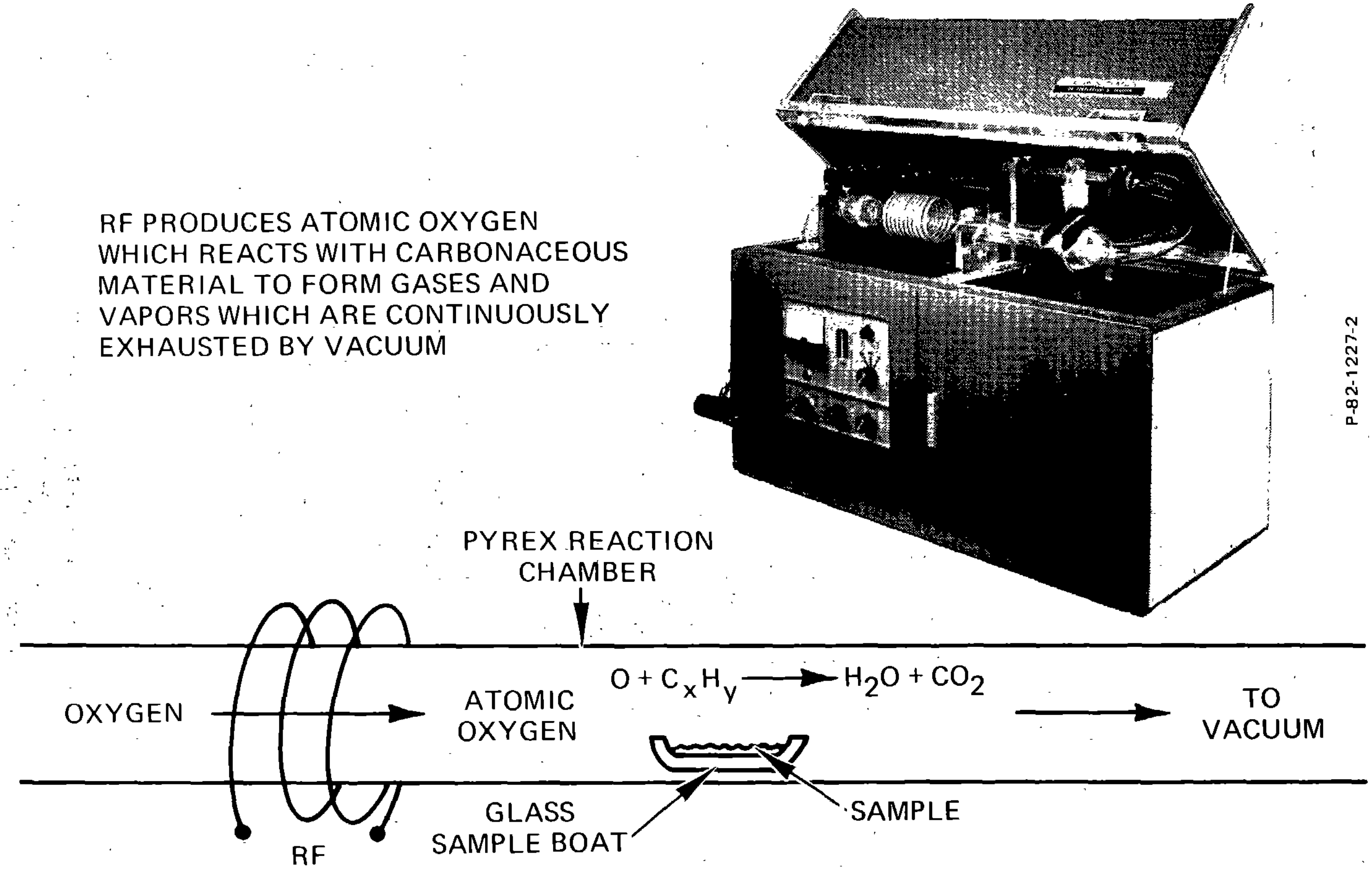


Figure 8-5 - Low Temperature Ashing

A series of tests was run to determine the organic content removal by the oxygen plasma on several types of samples. The removal rate varied according to sample type and state of subdivision:

Sample	Removal Rate mg/hr
Carbon Rod	
Small Piece (Large Area)	31
Large Piece (Small Area)	21
Phenolic Resin	>15
Filter Paper	40
Wear Debris	4

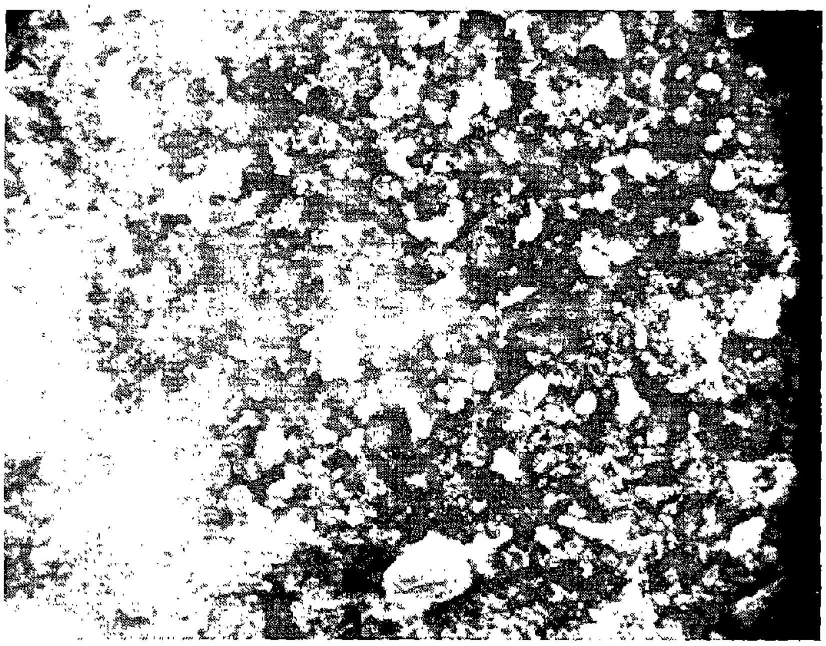
Carbon rod was the standard recommended by the instrument manufacturer who claimed a removal rate of 90 mg/hr. This rate was never obtained. For the carbon rod, the phenolic resin, and the filter paper, the removal rate was dependent on surface area exposed to the plasma. The wear debris, in spite of a large surface area, exhibited very low removal rates. Consequently, long periods were required for removal.

The LTA process removed 15 to 30 percent of the sample weight, which, in turn, effectively increased the concentration of the asbestos content for counting purposes, as performed later. Figure 8-6 shows LTA-treated wear debris as distributed on a 0.8μ Nuclepore filter. The large groups of asbestos fibers shown in Figures 8-4 and 8-6 are not typical; in almost all cases single fibers and fibrils exist and the larger groups are shown for illustrative purposes only.

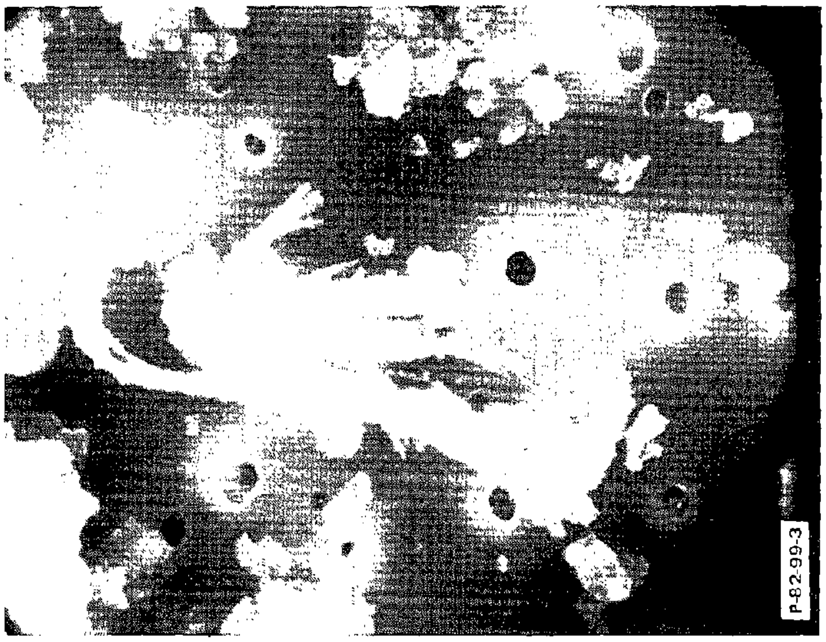
The second representative sample step is described in Sequence 7B of Appendix D. The appropriate LTA sample was taken in the following manner: approximately 10 fractions of approximately 0.05 mg each (material held on tip of fine spatula) were placed in a tiny platinum boat on a five-place analytical balance until 0.55 $\pm$ 0.05 mg, weighed to the nearest 0.01 mg, was obtained. This material was then suspended in a liquid and distributed onto a 0.2μ Nuclepore filter as outlined in Sequence 7B of Appendix D and shown in Figure 8-7. The manner in which the value of 0.55 $\pm$ 0.05 mg was obtained is described in the following section.

8.4.4 Sample Distribution for Microscopy

The amount of material to be examined by microscopy was arrived at by trial-and-error. A 47 mm filter loading of 10.0 mg was too great, as the smaller particles were not seen or separated from larger particles. The sample shown in Figure 8-6 was prepared with 7.0 mg loading and several areas of severe crowding or multi-layers of particles were seen. A further series of samples was made with filter loadings



(a) LTA Wear Debris on 0.8μ Nuclepore Filter - 500X



(b) Asbestos Particle Located in LTA Wear Debris - 5000X

Figure 8-6 - SEM Photomicrographs of LTA Wear Debris Samples

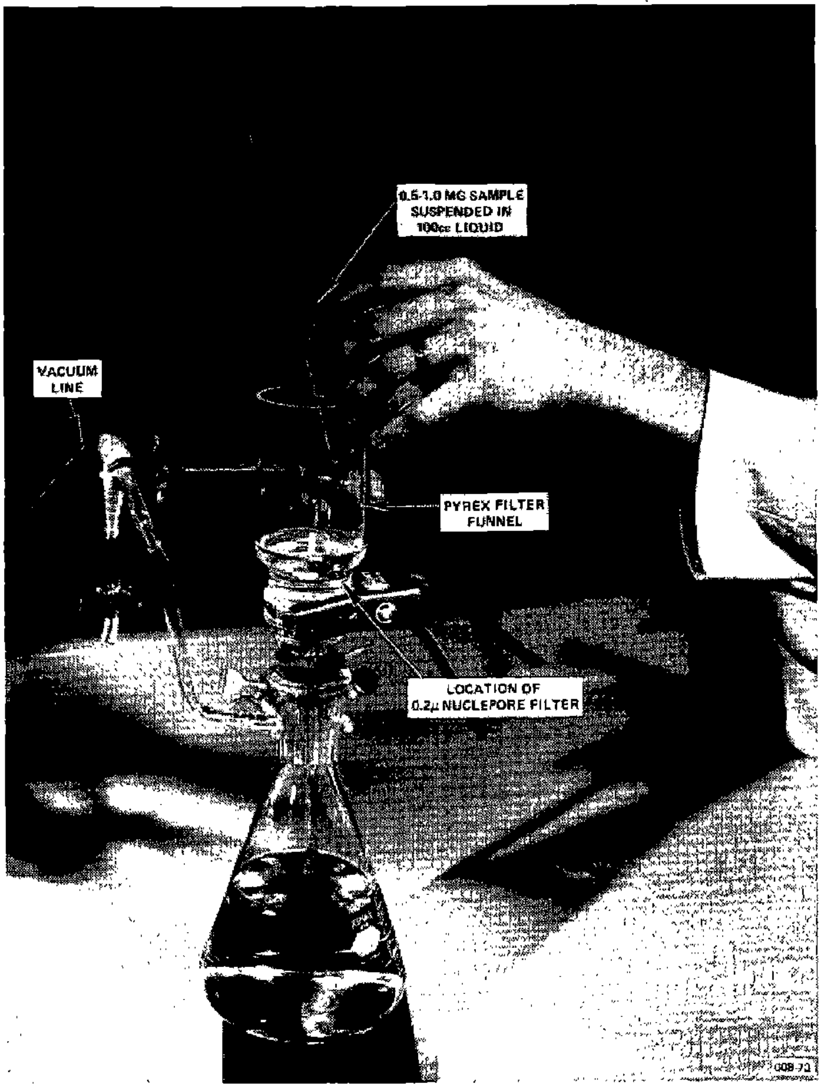


Figure 8-7 - Uniform Sample Distribution onto Filter

down to 1.0 mg. At the 1.0 mg level, the particles were sufficiently spread out to permit viewing of each particle by electron microscopy. However, to achieve consistently stable films, a further study was carried out (Appendix E) and it was found that good electron microscopy results could only be obtained by implementing the following changes in the analytical procedure:

- Use of a smaller grid opening (400 mesh screens) to give good support and higher thermal conductivity.
- Lower loading on filter (0.50 to 0.60 mg) for more uniform distribution.

- A second layer of carbon to effectively "sandwich" the wear debris for both strength of sample and thermal conductivity improvements.

In early tests, wear debris was collected on both Millipore and Nuclepore filters. The smaller particles entered into the fibrous network of the Millipore filters as shown by scanning electron microscopy. On the other hand, the Nuclepore membranes readily exhibited the collected wear debris on a relatively flat surface. To avoid future qualitative and quantitative problems with fiber identification, Nuclepore filters were therefore selected for all further work in this program.

8.4.5 Selected Microscopy Methods

8.4.5.1 Initial Studies and Rationale

A survey of the available analyses for asbestos particles in friction material wear debris or in ambient air samples was made. All methods found were satisfactory for total asbestos. All methods found were unsatisfactory for asbestos particle size distribution, as they all involved a particle size reduction step for transmission electron microscopy observation. Fiber bundles similar to those shown in Figure 8-6 did not permit sufficient electron beam penetration and good images could not be obtained for qualitative and quantitative observation when fibril ends were not present.

In the very early tests, wear debris from a sample dynamometer was collected on the filter train of the 8.0μ and 0.2μ Nuclepore filters. Both filters were examined by a combination of optical and transmission electron microscopy. The following observations were made:

- When the total airborne sample was small, the particulate distribution between the filters was almost even. As the total sample (sum of debris on both filters) became larger, the larger amount of debris remained on the 8.0μ filter. In effect, it became a finer filter and less material passed to the 0.2μ filter.
- The size distribution on the 8.0μ filter varied over a larger range; the material on the 0.2μ filter was finer and more uniform in size.
- Fibers were found on both filters; fibers up to 2.0μ diameter and 50μ long were located on the 8.0μ filter, and up to 0.9μ diameter and 3.6μ long on the 0.2μ filter. The electron beam could not penetrate the thicker fibers.
- Although many nonfibrous particles were checked for crystallinity by electron diffraction, very little crystallinity was found.

Additional particulate analyses were carried out for the airborne samples collected from the inertia dynamometer tests described in Section 6. The filters were examined "as collected", without any sample redistribution onto a single filter. The following observations were made:

- Asbestos fibers longer than 20 microns were obtained.
- Very fine fibrils were extremely difficult to detect in "as-collected" airborne wear debris.

Based on the above studies, it was deemed necessary to employ two magnifications. To detect fibers greater than 5μ, a magnification in the range 400 to 1000 diameters, was required. To detect the finer fibers and the ultimate fibrils, a magnification in the range 10,000 to 40,000 diameters was required.

The following optical plus transmission electron microscopy magnifications were selected:

	Fibers Detected (μ)	
	Minimum d x l	Maximum d x l
Transmission Electron at 22,000X	0.03 x 0.10	0.50 x 35
Optical (Phase Contrast) at 400X	0.50 x 1.50	10 x 100

8.4.5.2 Optical Microscopy Analysis for Asbestos

The U.S. Public Health Service procedure outlined in Section 8.3.3 was modified for this program. The procedure(8-1) called for Millipore filters and the fluid used for phase contrast had a refractive index of 1.460. In the Bendix procedure with Nuclepore Filters, a fluid matching one of the refractive indices of Nuclepore filters at 1.585 was substituted.

The procedure used is described in Sequence 8H of Appendix D. Figure 8-8 shows the microscopist behind the Reichert Zetopan as equipped with Heine phase contrast optics at 400 diameters. A typical photomicrograph (Figure 8-9) shows fiber among the remaining wear debris.

8.4.5.3 Transmission Electron Microscopy Analysis for Asbestos

The University of California School of Public Health procedure, also described in Section 8.3.3, was modified for this program. A magnification of 22,000 diameters was used instead of the prescribed 3000 diameters because of the difficulty in seeing fibers below 0.1μ in diameter.

Figure 8-8 - Phase Contrast Optical Microscopy at 400X

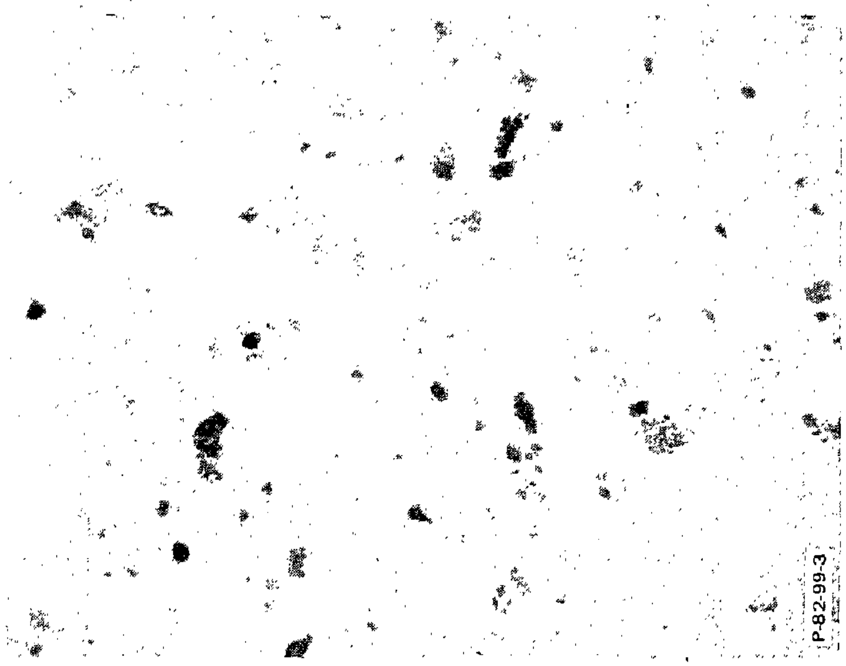


Figure 8-9 - Phase-Contrast Photomicrograph of Wear Debris - 400X

The procedure used is described in Sequence 8B of Appendix D. Figure 8-10 shows the Hitachi Type HU-125E transmission electron microscope used in this program. A typical photomicrograph (Figure 8-11) shows asbestos fiber among the remaining wear debris.

8.4.6 Calculations From Microscopy Results

8.4.6.1 Rationale and Microscopy Count Sheet

The ultimate asbestos fibril has been found to be circular in cross section[8-5]. When the wear debris was spread thinly over the flat Nuclepore filter membranes, each fiber remained flat when viewed in the microscope, so that its projected diameter and length

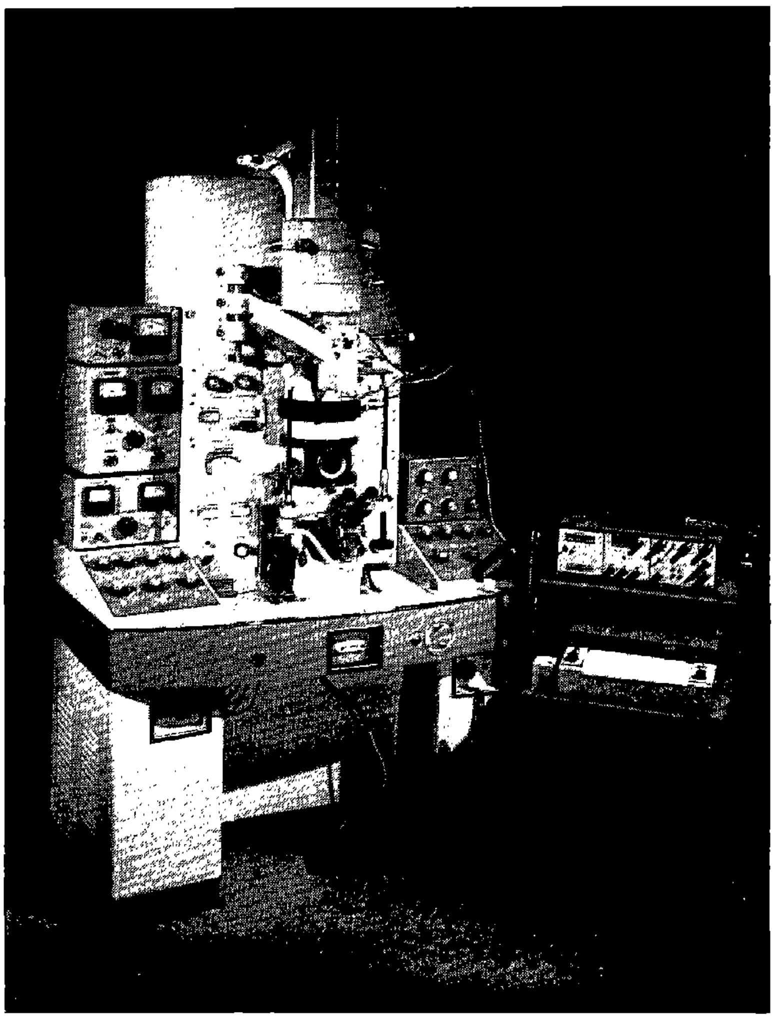


Figure 8-10 - Transmission Electron Microscope could be measured. The volume of each asbestos fiber was readily determined from the following formula:

$$V = \frac{\pi d^2}{4} \times \ell$$

where

V = volume of material

d = projected diameter measured

ℓ = length measured

When two or more fibrils make up the larger fiber bundles, a larger-than-actual projected diameter results. Even fibers with elliptical cross section were assumed to lay such that their largest diameter was parallel to the filter. In all cases, the volume calculated from the projected diameter and length was thus on the high side.

For each fibril or fiber found, it was necessary to determine its dimensions and calculate the volume of asbestos found. Because of the large number of fibers, this procedure became tedious. To simplify fiber sizing, a Microscopy Count Sheet was developed (Figure 8-12). The cross-hatched areas are the boxes which did not follow the definition of a fiber: the length was required to be three or more times greater than the diameter. Each fiber found by the appropriate microscopy method was classified into the proper box containing the projected diameter and length of the fiber in question. A typical microscopy count for a sample generated in this program is superimposed on Figure 8-12.

8.4.6.2 Sample Calculation

A typical calculation is carried out in the following manner. For each box, an average volume is calculated from the formula:

$$\overline{V} = \frac{\pi \overline{d^2}}{4} \times \overline{\ell}$$

where

$\overline{V}$ = average volume for box

$\overline{d^2}$ = average of diameter^2 for box

$\overline{\ell}$ = average length for box

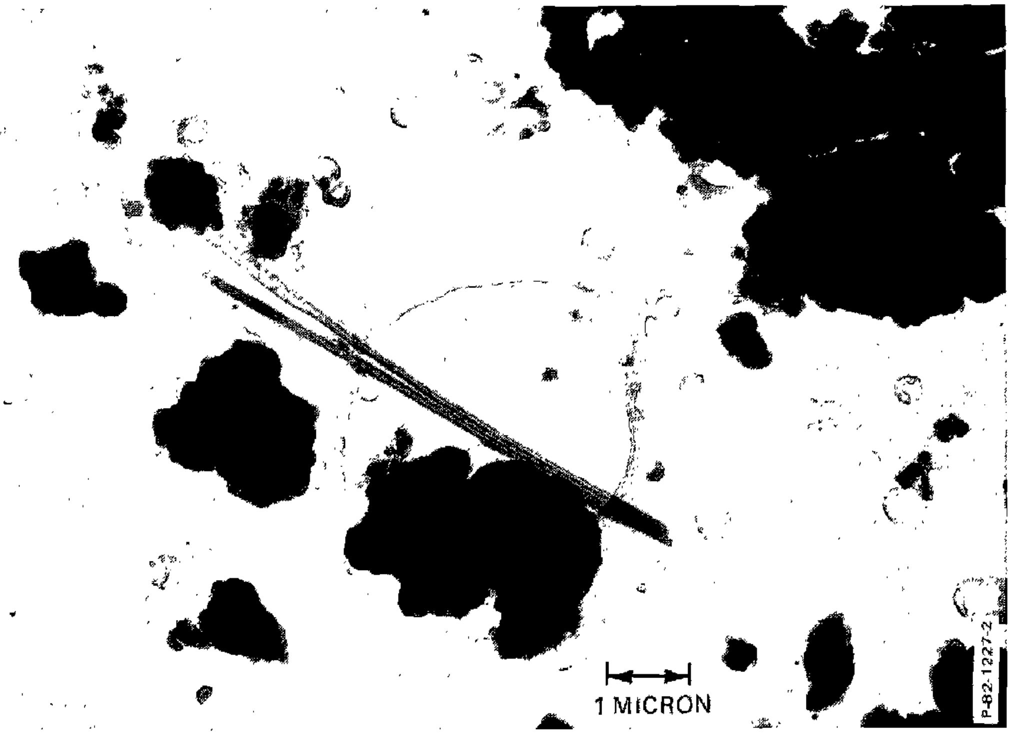


Figure 8-11 - Asbestos Fiber in Brake Emission

These values are given in Figure 8-13. Then it is necessary to multiply the number of fibers given in each box in Figure 8-12 by the volume given for the corresponding box as shown in Figure 8-13.

The typical microscopy count shown in Figure 8-12 is used to calculate asbestos content in the following manner. The fibers of each group are totaled as shown in Table 8-5. The total number of fibers per group (n) is then multiplied by the average volume per group ($\bar{V}$) to obtain the product (n x V). All products are then totalled to arrive at the total volume of asbestos detected.

Since only a fraction of the total area is actually scanned, the volume observed must be normalized to the entire area containing wear debris:

Total Fiber
Volume (by EM or OM)

$$= \text{Volume obtained (cc)} \times \frac{\text{Total Area of Filter}}{\text{(No. of Fields Counted)} \times \text{(Area of a Field)}}$$

$$= \Sigma\ (n \times \bar{V}) \times \frac{990\ \text{mm}^2}{\Sigma F \times \text{(Area of Field)}}$$

MICROSCOPY COUNT SHEET

Vehicle Test: 1
Schedule: A.B. BASELINE
Collector: RIGHT REAR BRAKE
Sample: SUMP
Date: 7-21-72

Total Sample Weight: 185.1 mg
LTA Weights (I/F): 38.8 / 31.2 mg
Count Weight: 0.62 mg
Comments:

22,000X

	FIBER DIAMETER (μ)	1	2	3	4	5	6	7	8	
		FIBER LENGTH (μ)								
	MIN / MAX	0.05 / 0.25	0.25 / 0.50	0.50 / 1.5	1.5 / 5.0	5 / 10	10 / 20	20 / 30	30 / 50	>50
11	0.02 / 0.03									
12	0.03 / 0.05	/ 1	// / 5							
13	0.05 / 0.08		/ //// 5	///// /////// 12	/ 1					
14	0.08 / 0.25		/ 1	////// /// 9	/ 1					
15	0.25 / 0.50									
16	0.50 / 1.0									

Date Counted: 7-28-72
EM Field Size: 3.0 x 3.0μ
No. of Fields: 200
15
18
33 fibers

400X

	FIBER DIAMETER (μ)									
		FIBER LENGTH (μ)								
	MIN / MAX		0.5 / 1.0	1.0 / 3.0	3.0 / 10.0	10 / 20	20 / 35	35 / 60	60 / 100	
25	0.50 / 1.0			/// ////// 9	///// //// 9		/ / 2			
26	1.0 / 2.0				/// // 6	/ 1				
27	2.0 / 3.0				/ 1	//// 4				
28	3.0 / 4.0									
29	4.0 / 5.0									
30	5.0 / 7.0									
31	7.0 / 10.0									
	>10									

Date Counted: 7-25-72
OM Field Size: 88 x 88μ
No. of Fields: 200
17
14
31 fibers

Microscopist: D. Jones

Figure 8-12 - Microscopy Count Sheet

FIBER VOLUME CALCULATION

$\times 10^{12}$ cc $V = 0.786 \times 10^{-12} \times \overline{d^2} \times \overline{\ell}$

22,000X

		FIBER DIAMETER (μ) MIN / MAX	1	2	3	4	5	6	7	8	
		FIBER LENGTH (μ)									
		MIN / MAX	0.05 / 0.25	0.25 / 0.50	0.50 / 1.5	1.5 / 5.0	5 / 10	10 / 20	20 / 30	30 / 50	>50
11		0.02 / 0.03	0.077 $\times 10^{-3}$	0.192 $\times 10^{-3}$	0.51 $\times 10^{-3}$	1.66 $\times 10^{-3}$	3.83 $\times 10^{-3}$	7.77 $\times 10^{-3}$			
12		0.03 / 0.05	0.20 $\times 10^{-3}$	0.50 $\times 10^{-3}$	1.34 $\times 10^{-3}$	4.25 $\times 10^{-3}$	10.0 $\times 10^{-3}$	20.0 $\times 10^{-3}$			
13		0.05 / 0.08	0.53 $\times 10^{-3}$	1.31 $\times 10^{-3}$	3.50 $\times 10^{-3}$	11.3 $\times 10^{-3}$	26.3 $\times 10^{-3}$	52.6 $\times 10^{-3}$			
14		0.08 / 0.25		10.15 $\times 10^{-3}$	27.1 $\times 10^{-3}$	88.0 $\times 10^{-3}$	203 $\times 10^{-3}$	406 $\times 10^{-3}$			
15		0.25 / 0.50			123 $\times 10^{-3}$	401 $\times 10^{-3}$	890 $\times 10^{-3}$	1.78	2.96	4.74	
16		0.50 / 1.0				1.72	3.97	7.96	13.3	21.2	

Date Counted:
EM Field Size: 3.0 x 3.0μ
No. of Fields:

400X

		FIBER DIAMETER (μ)	FIBER LENGTH (μ)								
		MIN / MAX		0.5 / 1.0	1.0 / 3.0	3.0 / 10.0	10 / 20	20 / 35	35 / 60	60 / 100	
25		0.50 / 1.0			0.982	3.19	7.30	13.5	23.3	39.3	
26		1.0 / 2.0				12.8	29.4	53.8	93.0	167	
27		2.0 / 3.0				33.2	76.7	141.0	243.0	409.0	
28		3.0 / 4.0				63.0	147.0	270	466	784	
29		4.0 / 5.0					241	433	765	1290	
30		5.0 / 7.0					436	805	1380	2.33 $\times 10^{3}$	
31		7.0 / 10.0						1.62 $\times 10^{3}$	2.89 $\times 10^{3}$	4.69 $\times 10^{3}$	
		>10									

Date Counted:
OM Field Size: 88 x 88μ
No. of Fields:

Microscopist:

Figure 8-13 - Fiber Volume Calculations

**** ASBESTOS ANALYTICAL RESULTS ****

EM SUB TOTAL = 0.5683E-06
OM SUB TOTAL = 0.8148E-06

VEHICLE TEST: 1
SCHEDULE: A. B. BASELINE
COLLECTOR: RIGHT REAR BRAKE
SAMPLE: SUMP

DATE: 7-21-72
NO.: 104

LTA(I)= 0.3880E-01
LTA(F)= 0.3120E-01

TOTAL = 0.1383E-05
COUNT WEIGHT = 0.6200E-03

ASBESTOS PERCENT = 0.1797

0.464E-16	0.0
0.681E-16	0.0
0.100E-15	0.0
0.147E-15	0.0
0.215E-15	0.550E 06
0.316E-15	0.0
0.464E-15	0.0
0.681E-15	0.165E 07
0.100E-14	0.0
0.147E-14	0.275E 07
0.215E-14	0.0
0.316E-14	0.0
0.464E-14	0.660E 07
0.681E-14	0.0
0.100E-13	0.0
0.147E-13	0.110E 07
0.215E-13	0.0
0.316E-13	0.495E 07
0.464E-13	0.0
0.681E-13	0.0
0.100E-12	0.550E 06
0.147E-12	0.0
0.215E-12	0.0
0.316E-12	0.0
0.464E-12	0.0
0.681E-12	0.0
0.100E-11	0.575E 04
0.147E-11	0.0
0.215E-11	0.0
0.316E-11	0.0
0.464E-11	0.575E 04
0.681E-11	0.0
0.100E-10	0.0
0.147E-10	0.447E 04
0.215E-10	0.0
0.316E-10	0.639E 03
0.464E-10	0.639E 03
0.681E-10	0.0
0.100E-09	0.256E 04
0.147E-09	0.0
0.215E-09	0.0
0.316E-09	0.0
0.464E-09	0.0
0.681E-09	0.0
0.100E-08	0.0

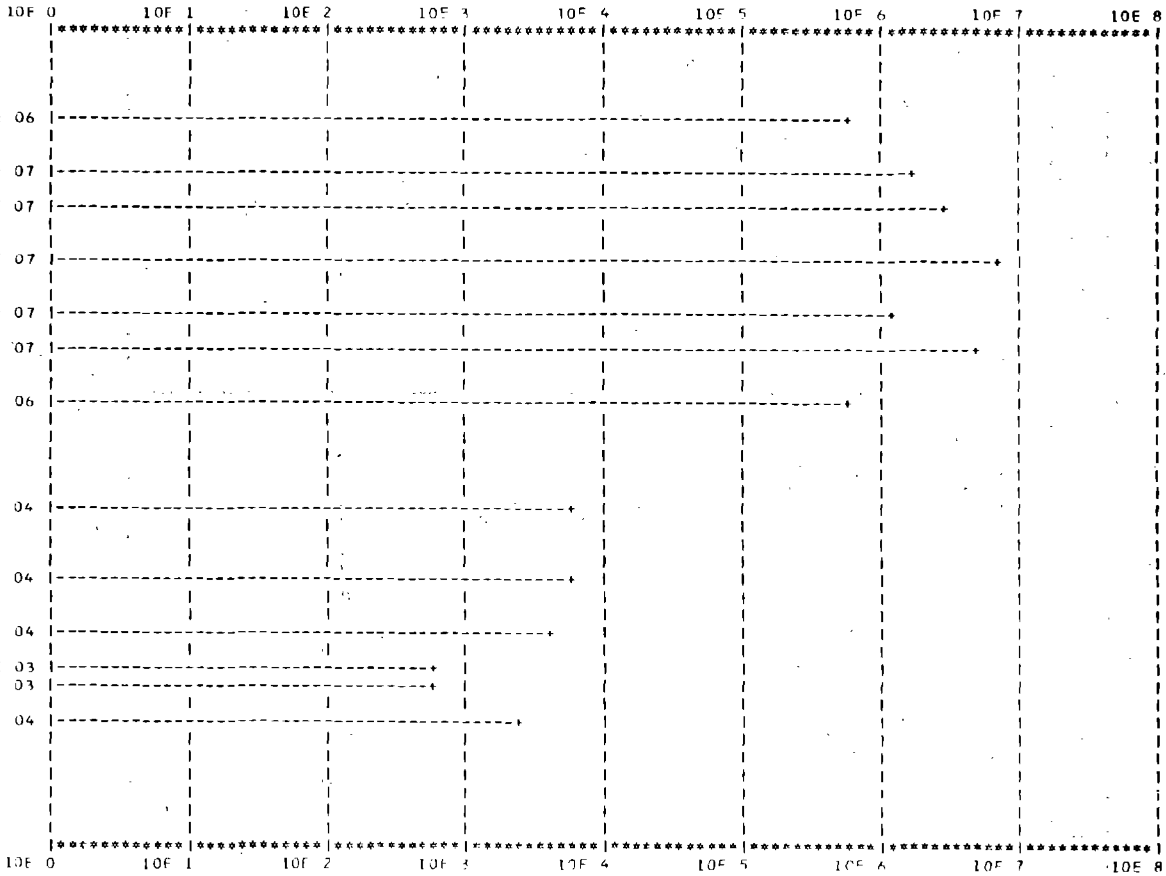


Figure 8-14 - Computer Printout of Asbestos Analytical Results

Table 8-5 - Sample Calculation

ELECTRON MICROSCOPY			OPTICAL MICROSCOPY		
Fiber Number (n) x	Fiber Volume ($\bar{V} \times 10^{-15}$ cc) =	$n \times \bar{V}$ ($\times 10^{-15}$ cc)	Fiber Number (n) x	Fiber Volume ($\bar{V} \times 10^{-12}$ cc) =	$n \times \bar{V}$ ($\times 10^{-12}$ cc)
1	0.20	0.20	9	0.982	8.92
3	0.50	1.50	9	3.19	28.7
5	1.31	6.55	2	13.5	27.0
12	3.50	42.0	5	12.8	64.0
1	11.3	11.3	1	29.4	29.4
1	10.2	10.2	1	33.2	33.2
9	27.1	243.0	4	76.4	305.0
1	88.0	88.0			
		$\Sigma\ n \times \bar{V} = 402.7$			$\Sigma\ n \times \bar{V} = 496.22$

ELECTRON MICROSCOPY

Total Volume_{EM}

$$= \frac{\Sigma\ (n \times \bar{V}) \times (\text{Area of filter})}{(\text{No. of fields}) \times (\text{Area of field})}$$

$$= \frac{402.7 \times 10^{-15}}{200} \times \frac{990 \times 10^{6}\ \mu^2}{3 \times 3\ \mu^2}$$

$$= 202 \times 10^{-9}\ \text{cc}$$

OPTICAL MICROSCOPY

Total Volume_{OM}

$$= \frac{\Sigma\ (n \times \bar{V}) \times (\text{Area of filter})}{(\text{No. of fields}) \times (\text{Area of field})}$$

$$= \frac{496.2 \times 10^{-12}}{200} \times \frac{990 \times 10^{6}\ \mu^2}{88 \times 88\ \mu^2}$$

$$= 316 \times 10^{-9}\ \text{cc}$$

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Total Volume $= (\text{Total Volume})_{EM} + (\text{Total Volume})_{OM}$

$= (202 + 316)\ 10^{-9}\ \text{cc} = 518 \times 10^{-9}\ \text{cc}$

Total Weight $= 518 \times 10^{-9} \times 2.50\ \frac{\text{gm}}{\text{cc}} \times 1000\ \frac{\text{mg}}{\text{gm}}$

$= 1.33 \times 10^{-3}\ \text{mg}$

Asbestos Percent $= \frac{0.00133}{0.62} \times \frac{312}{388} \times 100 = 0.173\%$

For the electron microscopy analyses at 22,000 diameters, the area of a field was $3 \times 3\ \mu^2$. For the optical microscopy analyses at 400 diameters, the area of a field was $88 \times 88\ \mu^2$. In electron microscopy analysis, 402.7×10^{-15} cc was found for 200 fields:

$$\begin{matrix}\text{Total Fiber} \\ \text{Volume (by EM)}\end{matrix} = 402.7 \times \frac{990\ \text{mm}^2}{(200) \times (3 \times 3\ \mu^2)} \times 10^{-15}\ \text{cc}$$

$$= 202 \times 10^{-9}\ \text{cc}$$

$$\begin{matrix}\text{Total Fiber} \\ \text{Volume (by EM)}\end{matrix} \times \begin{matrix}\text{Specific} \\ \text{Gravity}\end{matrix} \quad 2.56\ \frac{\text{gm}}{\text{cc}} = \text{Fiber Weight (by EM)}$$

$$202 \times 10^{-9}\ \text{cc} \times 2.56\ \frac{\text{gm}}{\text{cc}} = 0.00052\ \text{mg}$$

$$\begin{matrix}\text{Fiber Weight} \\ \text{(by OM)}\end{matrix} = 0.00081\ \text{mg}$$

$$\begin{matrix}\text{Combined total for all} \\ \text{asbestos found}\end{matrix} = 0.00133\ \text{mg.}$$

This amount of asbestos calculated is for debris which had been slightly concentrated in the LTA process. Thus the asbestos percent, as related to the original material, is obtained by the following expression:

$$\begin{matrix}\text{Asbestos} \\ \text{Percent}\end{matrix} = \frac{\text{Total Asbestos Found}}{\text{Count Weight}} \times \text{LTA Ratio } \frac{F}{I} \times 100$$

For the example given in Figure 8-12, the percent asbestos for the sump sample of the right rear brake collected for the A.B. Baseline Schedule of vehicle test 1 is found:

$$\begin{matrix}\text{Asbestos} \\ \text{Percent}\end{matrix} = \frac{0.00133}{0.62} \times \frac{31.2}{38.8} \times 100 = 0.173\ \text{percent}$$

8.4.6.3 Computerization of Calculations and Particle Size Distribution

The calculation of asbestos content was lengthy and thus susceptible to computational errors. Moreover, over 150 such calculations were anticipated for the program. A computer program was therefore developed in conjunction with the Count Sheet given in Figure 8-12. The uppermost horizontal row and the extreme left vertical column of markers are used to identify the box with its corresponding volume. The circled number is the number of fibers found which correspond to that volume. Unlike the manual calculation, grouping of boxes in threes is not required and for this reason the computer calculation is slightly different and slightly more accurate than the manual calculation.

The computer program is given in Appendix F. Figure 8-14 shows the computer printout for the sample calculation given in the previous section. The computer printout gives the asbestos percent = 0.179 percent, which compares with the manual calculation of asbestos percent = 0.173 percent.

8.4.7 Possible Sources of Error

The possible sources of error for the sampling and analysis of particulate wear debris are listed in Table 8-6.

The possible sources of error associated with sample processing were minimized through the use of statistical methods. For sample selection, two stages of representative sampling took place: weighing prior to sample low temperature ashing, and weighing for distribution onto the filter. Uniformity of sample distribution was checked by low power optical microscope observation immediately after distribution. This was further checked by the microscopy results as shown in Figure 8-12. Just under the number of fields reported for the electron microscopy results, the notation used shows 15 fibers found in 100 fields examined on 2 grids from one side of the filter, while 18 fibers were found for 100 fields examined on 2 grids from the other half on the filter. Also, for the optical microscopy results, 17 fibers were found in 100 fields on a sample taken from one side of the filter, while the other side yielded 13 fibers. These distributions were typical.

As indicated in Appendix E, a series of tests was run to insure good samples for electron microscopy. Membrane shrinkage did not occur and membrane curling was minimized. No observations in the electron microscope were taken near membrane edges. The sample distribution was finalized after more than ten different sample weights were examined and then several different samples at the same sample weight gave reproducible films in terms of stability and counting.

Table 8-6 - Possible Sources of Error

SAMPLE PROCESSING

- Low Temperature Ashing
  - Sample Selection
  - Extent of Ashing
  - Weighing
- Sample Distribution
  - Sample Selection (From Vial)
  - Sample Weighing
  - Characteristics of Sample and Variations in Size Distribution
  - Loss through Filter
  - Filter/Funnel Interface Effects
- Sample Handling
  - Air-Borne Dust Contamination
  - Static Electricity
  - Air Currents

MICROSCOPIC METHODS

- Sample Preparation
  - Sample Identification
  - Sample Redistribution during Cutting
  - Membrane Stretching, Shrinkage, or Curling
- Sample Counting
  - Depth of Field
  - Width x Length Estimates
  - Large Fiber Contributions
  - Fiber Identifications (Asbestos Versus Olivine)
  - Magnification Variations
  - Statistics

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Perhaps the largest sources of error occur in the sample counting procedure, for the following reasons:

- Width and length estimates of fibers and their insertion into the proper box in Figure 8-12 (a borderline diameter such as 0.05 μ which is between lines 12 and 13 gives an average volume difference of approximately 3).
- Fiber identification difficulty, especially in optical microscopy (asbestos or olivine).
- Number of fibers found and their statistics.

These errors were minimized by counting a large number of fibers and/or fields, whichever came first. The target for fiber counting was 100 fibers in 100 fields in both electron and optical microscopy. This target was rarely obtained because of the very low content of asbestos present in the sample. A maximum number of fields to be counted for low fiber concentrations was also established (200 EM fields and 300 OM fields), to avoid unnecessary delays for very low concentrations.

The largest effect found on the asbestos analysis was the occurrence of a large fiber. Its volume contribution significantly increased the contribution, in either microscopy method, by 100-200 percent. This could give up to a 50 percent change in the final calculation. If additional fields were counted or a replicate analysis made, a comparable fiber was usually not found. The large fiber was thus considered an "outlier" and was not used in the calculations. In some instances, more than one large fiber was found in a sample. Replicate analyses did not yield similar fibers and the asbestos emissions result was significantly different as shown in Table 8-7 for the following sample: Vehicle Test 1, Detroit Traffic Schedule, right front brake, sump sample (Example 1).

The precision in the asbestos analytical results can be estimated by considering the replication data given in Table 8-7. The percent deviations range from 0 to 79 percent; the average is ±27 percent. On the other hand, Figure 8-15 shows the variation of the maximum deviation (given in Table 8-7) with the asbestos percent found. The data show that the maximum deviation for results with asbestos contents above approximately 0.10 percent have a maximum envelope at approximately 20 percent, with averages at 12-15 percent. The maximum deviation increases for asbestos content below 0.10 percent, where errors for the small amounts of asbestos emissions become less significant.

8.5 ANALYSIS OF GASEOUS EMISSIONS

8.5.1 Method of Analysis

The gas collection system (described in Section 5.4) was designed to collect and separate condensable and noncondensable gases from the carrier air. Because of the high vapor pressure of the noncondensable gases in the activated-charcoal traps, storage took place at

Table 8-7 - Extent of Error in Asbestos Emissions Analytical Results

EXAMPLE NUMBER	SAMPLE	ASBESTOS PERCENT	AVERAGE	MAXIMUM DEVIATION	PERCENT DEVIATION
1	Vehicle Test 1 Detroit Traffic Right Front Brake Sump Sample	0.247* 0.631 0.186	0.355	0.276	±79%
2	Vehicle Test 1 Detroit Traffic Right Front Brake Surfaces	0.137* 0.085 0.091 0.116	0.107	0.022	±21%
3	Vehicle Test 1 Detroit Traffic Right Front Brake Airborne	0.052* 0.025 0.085 0.068	0.056	0.031	±55%
4	Vehicle Test 1 A.B. Baseline Right Rear Brake Airborne	0.432* 0.554	0.493	0.061	±21%
5	Vehicle Test 3 Detroit Traffic Right Front Brake Surfaces	0.013* 0.034	0.023	0.011	±48%
6	Vehicle Test 3 Detroit Traffic Right Rear Brake Surfaces	0.057* 0.045	0.051	0.006	±12%
7	Vehicle Test 3 Final Baseline Right Front Brake Surfaces	0.087* 0.061	0.074	0.013	±18%
8	Vehicle Test 3 Final Baseline Right Rear Brake Sump	0.512* 0.386 0.511	0.470	0.084	±18%
9	Vehicle Test 3 Final Baseline Right Rear Brake Surfaces	0.237*	0.228	0.010	± 5%
10	Cumulative for Vehicle Tests 1, 2, and 3 Clutch Surfaces	0.047 0.047	0.047	0.000	0

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*Result reported in Tables 9-16, 9-17, and 9-18.

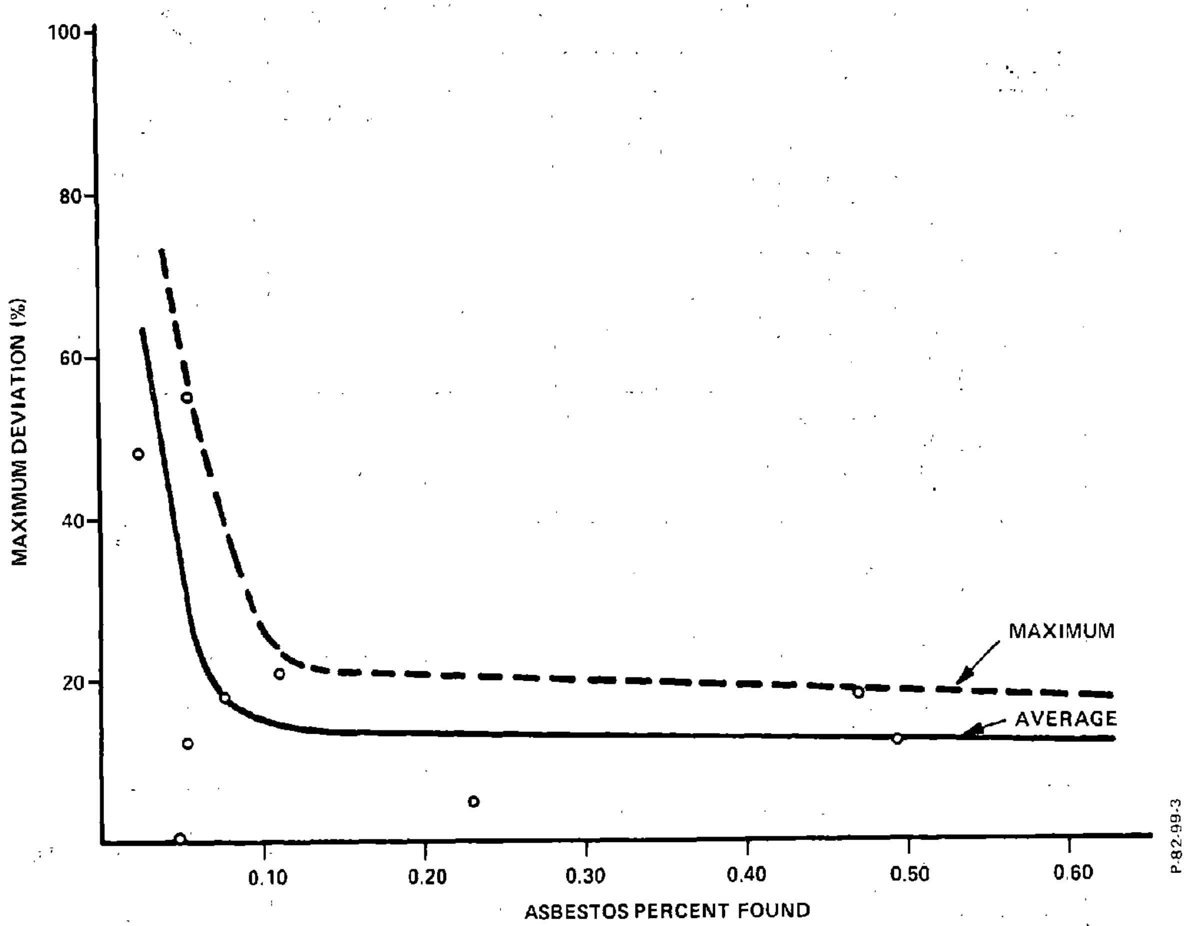

Figure 8-15 - Variation of Maximum Deviation of Asbestos Analytical Results with Asbestos Percent Found

-70°C with solid carbon dioxide packed around the traps. The analytical procedures are given in Appendix D. The primary method of analysis was gas chromatography for both the noncondensable and condensable gases.

8.5.2 Gas Handling System

The gas handling system used for the gas analysis is shown in Figure 8-16. The system included various sections designed to perform the following tasks:

- Gas inlet and fraction traps - used to separate air from the gases of interest.
- Toepler pump and gas buret - used to transfer the gases and measure their volume.
- Gas chromatograph transfer U-tube - used with gas buret and Toepler pump to inject a sample into the gas chromatograph (Figure 8-17).

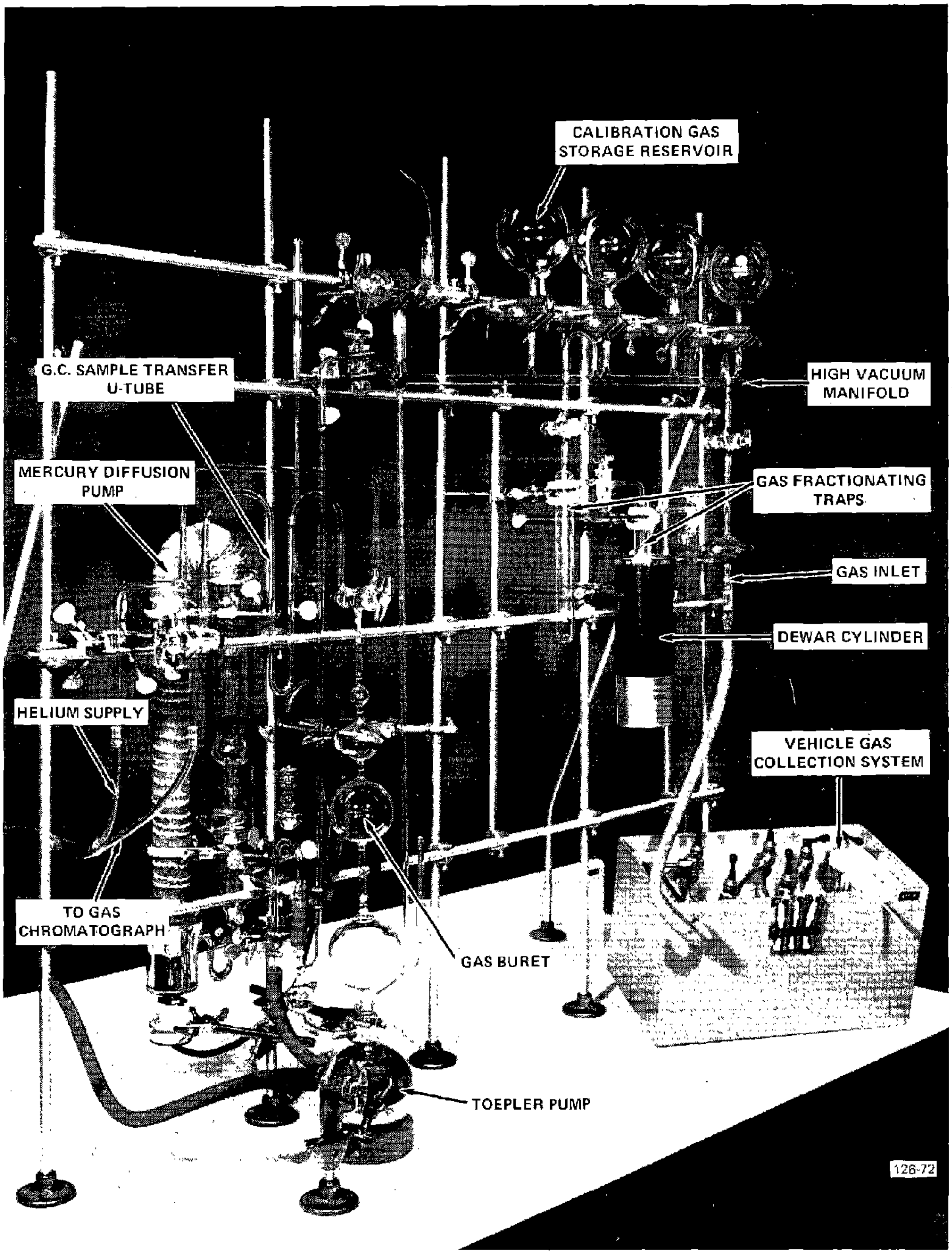

Figure 8-16 - Gas Handling System

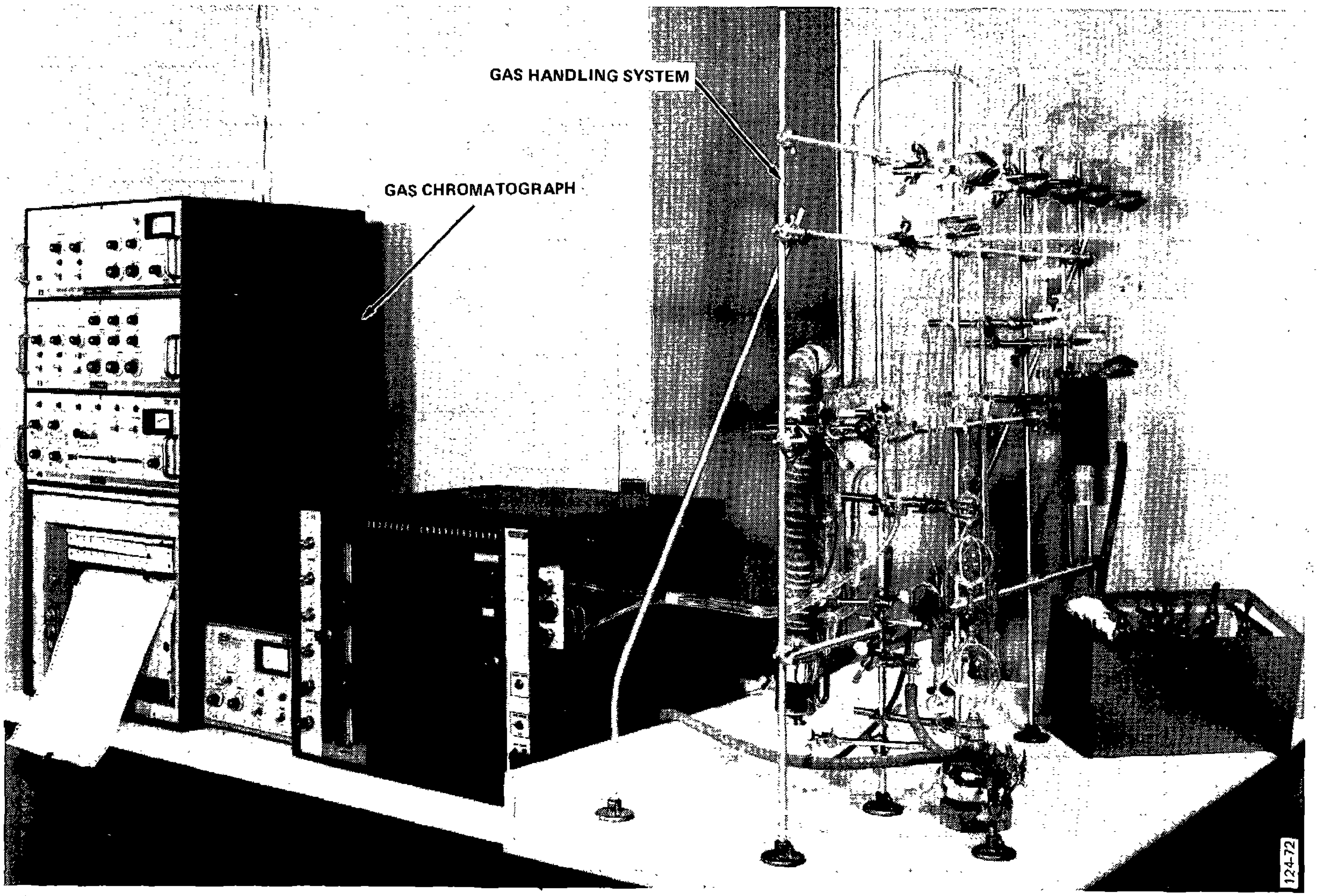

Figure 8-17 - Gas Handling System and Gas Chromatograph

- Calibration gas storage volumes - used to store pure gases or known mixtures which were used to calibrate the gas chromatograph.

The noncondensable gases were to be handled first. The complete step-by-step procedure is described as Sequence 10A in Appendix D. The condensable gases were then handled and their procedure is described as Sequence 10B in Appendix D.

8.5.3 Calibration of Gas Chromatograph

Prior to any analyses of samples generated by the vehicle, it was necessary to check out the gas handling system and calibrate the gas chromatograph. The gas handling system was set up in good working order. A calibration gas from one of the gas storage volumes was expanded into the high-vacuum manifold. By means of the Toepler pump, all of the sample could be collected and measured in the gas buret. The sample was then introduced into the G.C. transfer U-tube. The helium flow of the gas chromatograph was diverted so that the volume of gas in the gas chromatograph transfer tube could then be introduced directly into the gas chromatograph. The volume of gas introduced was calculated and the gas chromatograph detector response was determined. For a series of different volume sizes added to the gas chromatograph, a calibration curve could be made. Figure 8-18 is the typical detector response calibration curve obtained for carbon dioxide. Similar curves were prepared for other gases expected.

The retention data for the column used were obtained in the following manner. A gas mixture containing air (nitrogen and oxygen), carbon monoxide, methane, carbon dioxide, water, and propane was prepared exterior to the system. The mixture was stored in a separate volume. Small samples could be introduced through the gas inlet of the gas handling system. The sample was collected in the gas buret and transferred to the gas chromatograph. Several different temperature programs for the gas chromatograph column were evaluated in order to obtain a reproducible program which would elute all gases predictably and well separated. Figure 8-19 shows the typical retention time calibration for low molecular weight gases which may be present in the noncondensable gas traps. The components were separated on a column 6 feet long and 0.125 inch O.D., packed with Porapak Q. The column was initially cooled to less than -70°C with dry ice. This condition was needed to separate N_2, O_2, and CO. The column temperature was then raised rapidly to 30°C to elute CH_4 and CO_2. The column was then heated to 180°C at 10°C/min to elute water, C_3's, and C_4's.

8.5.4 Problems and Interferences

In Section 6.2.3, the integrity of the rotating seal was discussed along with its leak rate as measured under both static and dynamic conditions. It was impossible to eliminate the leak completely. Under static conditions, the flow through the seal was $\sim$137 cc/min. This

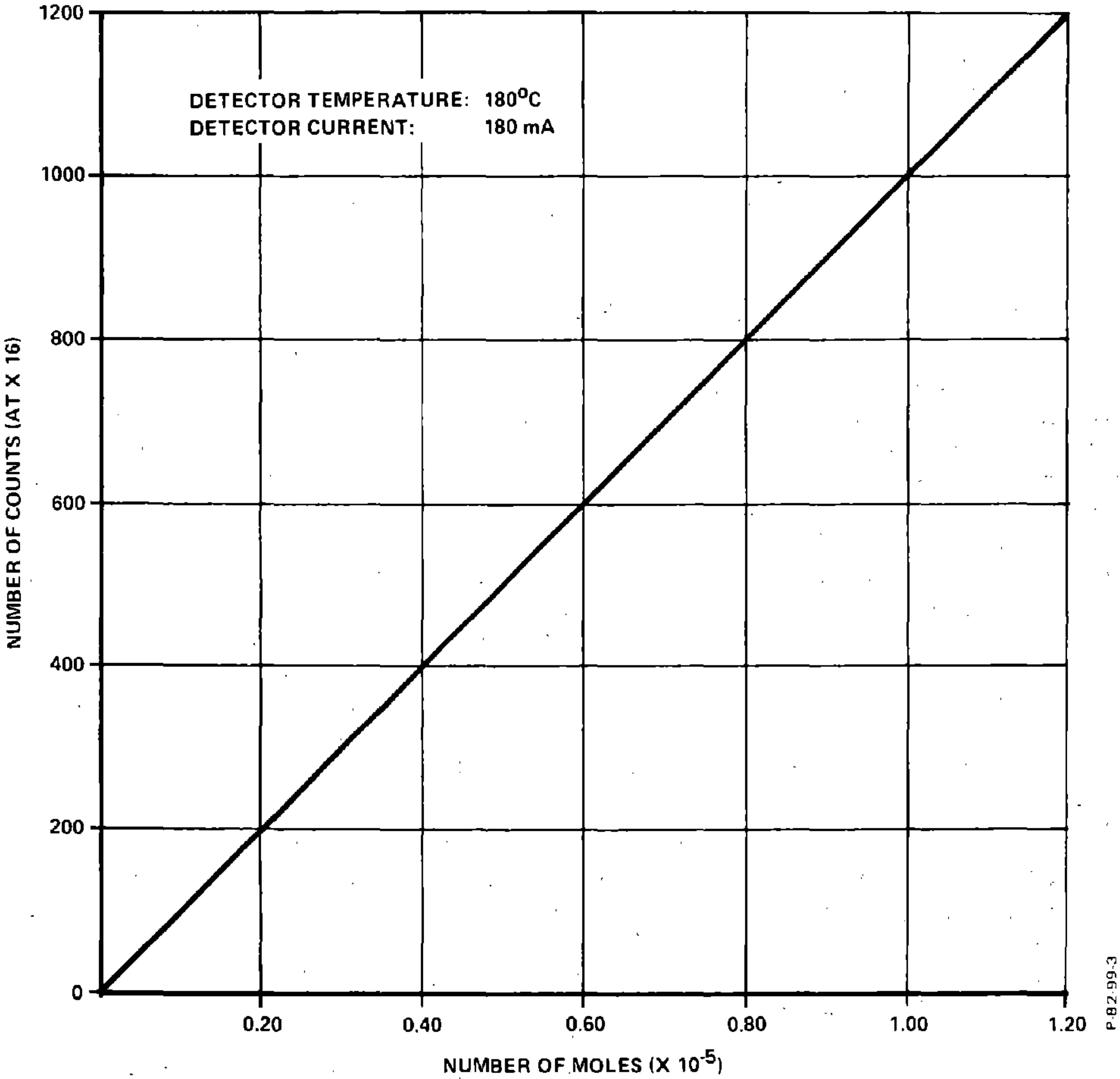

Figure 8-18 - Detector Response for Carbon Dioxide

improved to about 50 cc/min under the most optimum conditions. However, in all cases there was a gas flow through the rotating seal into the emissions collection system.

The rotating seal was downstream of the gas drier and carbon dioxide removal bed (described in Section 5.2.1). Thus the air entering the rotating seal contained the normal atmospheric components including carbon dioxide and water in addition to oxygen, nitrogen, and argon. In heavy traffic, measurable amounts of carbon monoxide and nitrogen oxides were also expected to be present. The large amounts of carbon dioxide and water obtained proved to be the major problem when the gases were collected at low gaseous emission concentrations such as in the

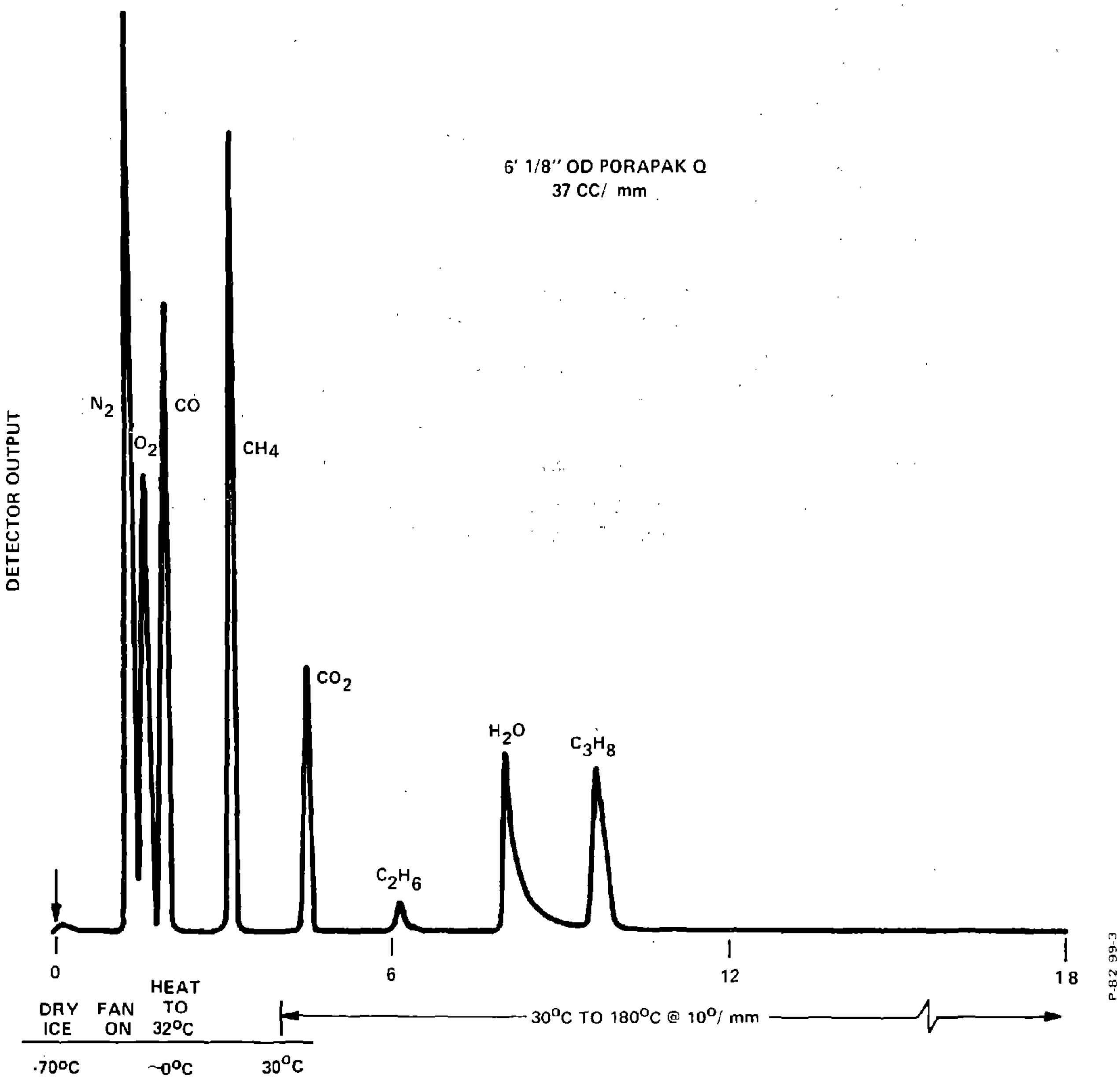

Figure 8-19 - Typical Calibration Chromatogram for Low Molecular Weight Gas

Detroit Traffic Test. During the later stages of the program, attempts were made to circumvent the carbon dioxide and water problems by selectively collecting gases only during periods when gas emissions were expected to be adequate, such as the fade tests.

8.6 REFERENCES

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SECTION 9

VEHICLE TEST RESULTS

9.1 VEHICLE OPERATIONS

9.1.1 Test Scheduling and Problems Encountered

Early in the program, it was estimated that approximately 38 days would be required to complete each vehicle test. This estimate was based on the optimistic assumption that the vehicle measurements procedure (take emissions samples, measure wear, inspect system, and replace worn parts) would require 1.5 days.

Tables 9-1, 9-2, and 9-3 are the actual versus estimated test schedules for vehicle tests 1, 2, and 3, respectively. Vehicle test 1 took 56 days because of the problems listed. Moreover, the measurements sequence actually required approximately two days. In addition, approximately one-half day was lost per schedule because of rain (the summer of 1972 was the wettest summer in recent history). The sum of the additional one-half day for measurements plus the one-half day for rain loss gave an average of an additional one day per schedule, or an additional seven days per vehicle test. Thus, the addition of seven days to the estimate of 38 days gave a value of 45 days, achieved in vehicle tests 2 and 3.

Near the end of vehicle test 3, there was a very good chance of finishing in approximately 42-43 days. However, melting snow and freezing rain made the driving conditions hazardous at times. Thus two days were lost, and the program was completed just prior to the even more wintry weather which began in late November in the Detroit area.

Some of the problems encountered in the program and their solutions can be summarized as follows:

- During the 10-stop fade schedule of vehicle test 1, the hardened steel ring which rotates aginst the Teflon seal slipped from its anchored position after shearing the locking pins. The leak thus created was detected immediately after the fade stops and prior to the reburnish. The ring was reanchored and no further problem was encountered during the 15-stop fade or any further test schedule.
- During the Detroit traffic schedule of vehicle test 1, water was found in the right rear brake collector. This was pulled in through the rotating seal. This problem was not encountered again, as the vehicle was not operated during heavy rain.

Table 9-1 - Actual Versus Estimated Test Schedules for Vehicle Test 1

TEST SCHEDULE	ESTIMATED TIME (DAYS)		ACTUAL TIME (DAYS)			REMARKS OR PROBLEMS
			START	FINISH	TOTAL	
Burnish Measurements*	2.0 1.5	3.5	5/1	5/10	8	• Heaters shorted. • Invertor failed. • Loose collector screws. • Slow silicone cure.
A. B. Baseline Measurements	3.0 1.5	4.5	5/11	5/18	6	
Detroit Traffic Measurements	12.0 1.5	13.5	5/19	6/13	20	• Burned-out heater. • Water in rear collector (due to rain). • Replaced rear seal. • Burned air line. • Replaced filters. • Rain - test stopped. • Slow silicone cure.
10-Stop Face Reburnish Measurements	1.5 1.0 1.5	4.0	6/14	6/21	6	• Rain. • Slow silicone cure. • Burned-out T.C. • Measurements - fronts only. • Rotor ring slippage.
A. F. Baseline Measurements	3.0 1.5	4.5	6/22	6/29	6	• Rain.
15-Stop Fade Reburnish Measurements	1.0 1.0 1.5	3.5	6/30	7/5	5	
Final Baseline Measurements	3.0 1.5	4.5	7/6	7/12	5	
		38.0			56	

*Take emissions samples, measure wear, inspect systems, replace worn parts.

Table 9-2 - Actual Versus Estimated Test Schedules for Vehicle Test 2

TEST SCHEDULE	ESTIMATED TIME (DAYS)		ACTUAL TIME (DAYS)			REMARKS OR PROBLEMS
			START	FINISH	TOTAL	
Burnish Measurements*	2.0	3.5	7/13	7/17	4	
A. B. Baseline Measurements	3.0 1.5	4.5	7/18	7/21	4	
Detroit Traffic Measurements	12.0 1.5	13.5	7/24	8/15	18	• Rain. • T/C replaced. • Inverter malfunction.
10-Stop Fade Reburnish Measurements	1.5 1.0 1.5	4.0	8/16	8/21	4	
A. F. Baseline Measurements	3.0 1.5	4.5	8/22	8/29	6	• Rain. • T/C replaced.
15-Stop Fade Reburnish Measurements	1.0 1.0 1.5	3.5	8/30	9/6	4	
Final Baseline Measurements	3.0 1.5	4.5	9/7	9/13	5	• Lost pressure on 11th circuit. Brake fluid in collector. Test terminated.
		38.0			45	

*Take emissions samples, measure wear, inspect systems, replace worn parts.

Table 9-3 - Actual Versus Estimated Test Schedules for Vehicle Test 3

TEST SCHEDULE	ESTIMATED TIME (DAYS)		ACTUAL TIME (DAYS) START	FINISH	TOTAL	REMARKS OR PROBLEMS
Burnish Measurements*	2.0 1.5	3.5	9/18	9/21	4	• Rain.
A. B. Baseline Measurements	3.0 1.5	4.5	9/22	9/28	5	
Detroit Traffic Measurements	12.0 1.5	13.5	9/29	10/23	17	
10-Stop Fade Reburnish Measurements	1.5 1.0 1.5	4.0	10/24	10/26	3	
A. F. Baseline Measurements	3.0 1.5	4.5	10/27	11/2	5	
15-Stop Fade Reburnish Measurements	1.0 1.0 1.5	3.5	11/3	11/8	4	
Final Baseline Measurements	3.0 1.5	4.5	11/9	11/17	7	• Freezing rain. • Icy roads.
		38.0			45	

*Take emissions samples, measure wear, inspect systems, replace worn parts.

- During the final baseline schedule of vehicle test 2, pressure was lost for the rear brakes and brake fluid was found in the collector. The combined sump and surfaces sample, for the eleven completed circuits, was salvaged by filtering and repeatedly washing the particulates to remove the brake fluid. The linings were "destroyed" as the fluid could not be removed completely. This problem was not encountered again.

9.1.2 Mileage Accumulations

Table 9-4 lists the mileage accumulations for each schedule. The A.B. Baseline, A.F. Baseline, and Final Baseline were run according to the same schedule, repeated at different times within the overall vehicle test program. The average baseline mileages varied from 343 to 348 miles and the maximum variation between vehicle tests was ± 5.7 percent. This range for the baseline schedules could also be compared to one-fourth of the Detroit traffic test for which the average was 352 miles (1408 ÷ 4) and for which the overall variation was ± 3.8 percent. The overall variation for the total mileage accumulation of all three vehicle tests was very low at ± 2.4 percent. These mileage variations were primarily due to the varying times taken to reach the Detroit traffic circuit. Normally only three round trips were required to obtain the twelve circuits. Rain, seal failure, thermocouple malfunctions, and other minor difficulties which required a premature return to base added to the minimum mileage possible.

9.1.3 Reporting of Vehicle Test Data

The data for each vehicle test are accumulated in a separate volume which includes a section for each test sequence: Burnish; A.B. (After-Burnish) Baseline; Detroit Traffic; 10-Stop Fade; A.F. (After-Fade) Baseline; 15-Stop Fade; and Final Baseline. Each section includes the following data sheets: Vehicle Log Sheet; supplementary vehicle data sheets such as Detroit Traffic data sheets; Wear Sheet - Front Axle; Wear Sheet - Rear Axle; Collection of Brake Emissions (Right Side); Collection of Brake Emissions (Left/Control Side); and Test Summary Sheet.

The complete list and examples of each type of data sheet are included in Appendix G.

9.2 PERFORMANCE OF EMISSIONS COLLECTION SYSTEMS

9.2.1 Rotating Seal Life

The success of the vehicle tests depended heavily on the proper operation of the rotating seals. Table 9-5 is a running log of rotating seal mileages (life) obtained during the vehicle test program. The original intent was to change the rotating seals at the start of each test and prior to the 10-Stop Fade. Both premature seal failure and the unexpected fact that disastrous rotating seal wear did not occur during the fade led to abandonment of that plan.

Table 9-4 - Summary of Vehicle Mileage Accumulations

Schedule	Test	Miles	Average Miles	Maximum Deviation	Percent Deviation
Burnish	1 2 3	174 127 100	134	34	
A.B. Baseline	1 2 3	328 348 368	348	20	5.7
Detroit Traffic	1 2 3	1439 1430 1355	1408	53	3.8
10-Stop Fade	1 2 3	47 53 58	53	6	
A.F. Baseline	1 2 3	356 339 347	347	9	2.6
15-Stop Fade	1 2 3	47 79 52	59	20	
Final Baseline	1 2 3	352 326 352	343	17	4.9
Totals	1 2 3	2756 2702 2632 8090	2697	65	2.4

Table 9-5 - Running Log of the Rotating Seals Mileages Obtained in the Vehicle Test Program

Test Schedule	MK III Front Collector			MK III Rear Collector			Comments
	Vehicle Test 1	Vehicle Test 2	Vehicle Test 3	Vehicle Test 1	Vehicle Test 2	Vehicle Test 3	
Pre-Test	126						
Burnish	174	127	100	174	127	100	Test 1: OK Test 2: OK Test 3: OK
A. B. Baseline	328	348	368	328	348/475	368	Test 1: OK Test 2: Rear seal failed and replaced after 475 miles. Test 3: OK
Detroit Traffic	1431/2059	1430/1965	1355	731/1233 700	1430	103/1315 62/62 1190	Test 1: Rear seal replaced after 1233 miles. Front seal replaced after 2059 miles. Test 2: OK Test 3: Rear seal replaced after 103 miles. Front seal replaced after 62 miles - "out-of-round."
10-Stop Fade	47	53	58	47	53/1483	58/1248	Test 1: OK Test 2: Front seal replaced after 1958 miles. Rear seal failed and replaced after 1483 miles. Test 3: OK
A. F. Baseline	356	339/392	347/2664*	356	339	347	Test 1: OK Test 2: Front seal failed and replaced after 392 miles. Test 3: Front seal replaced after 2664 miles.
15-Stop Fade	47	12/12 67	52	47	79	52	Test 1: OK Test 2: Front seal failed and replaced after 12 miles. Test 3: OK
Final Baseline	353/815	326/393	352/404	353/1515	326/744	352/751	Test 1: Front seal replaced after 815 miles. Rear seal replaced after 1515 miles. Test 2: OK, seals used to start Test 3. Test 3: OK
Total Miles	2756	2702	2632	2756	2702	2632	

*Includes 393 Miles from Test 2

Table 9-6 summarizes the rotating seal life in miles obtained for each seal during the three vehicle tests. These data were used to obtain a maximum average life for each rotating seal.

Seven rotating seals were used on the front disc brake collector. They were replaced at different mileage accumulations as follows:

- Two seals failed after 12 and 329 miles.
- Three seals survived 1965, 2059, and 2664 miles and were replaced as worn, but not failed.
- Two seals were used for 815 and 404 miles and were replaced although they were not completely worn or failed after vehicles tests 1 and 3, respectively.

Eight rotating seals were used on the rear drum brake collector. They were replaced at different mileage accumulations as follows:

- Three seals failed after 62, 475, and 1483 miles.
- Four seals survived 1233, 1515, 1315, and 1248 miles and were replaced as worn, but not failed.
- One seal survived 751 miles and was removed in good condition after the third vehicle test.

9.2.2 Operating Temperatures

9.2.2.1 Normal Brake Stops

Throughout the vehicle tests, it was necessary to monitor the temperatures at all four wheels. The driver was instructed to take specified actions when greater than desired temperature differences occurred. For example, during the Detroit Traffic Circuits, the maximum normal operating temperature was 330°F before proceeding. These cool-down periods were seldom necessary.

The effectiveness of the thermal control aids attached to the right front brake described in Section 5.5.3 is shown in Table 9-7. The ΔT = 200 to 250°F shown for the initial burnish was reduced to a ΔT = 115 to 160°F. Most important was the reduction of the right front brake operating temperature from about 400°F to about 300°F.

Since approximately 90 percent of the test miles were driven on the Detroit Traffic circuit, it was necessary to monitor the temperatures obtained and maintain test reproducibility. Although the temperatures did vary slightly, the normal operating range for the right front brake was 260 to 300°F while the normal operating range for the right rear brake was 170 to 200°F. The brake shrouding did not present any difficulties on hot days. Table 9-8 illustrates the brake temperatures measured during four consecutive Detroit Traffic Circuits on a hot

Table 9-6 - Rotating Seal Life (Miles)

VEHICLE TEST	SEAL INSTALLATION	FRONT DISC BRAKE	REAR DRUM BRAKE
1	1	F1 2059	R1 1233
	2	F2 815	R2 1515
2	3	F3 1965	R3 475
	4	F4 392	R4 1483
	5	F5 12	R5 (744)*
	6	F6 (393)*	
3	5 (cont'd)		R5 1315
	6 (cont'd)	F6 2664	R6 62
	7	F7 404	R7 1248
	8		R8 751
	Maximum Expected Life (miles)	2059 1965 Average: 2664 2229	1233 1515 1483 Average: 1359 1315 1248

*Continued usage into Vehicle Test No. 3.

Table 9-7 - Brake Temperatures During Burnish Tests (°F) (Vehicle Test 1)

	FRONT DISC BRAKE			REAR DRUM BRAKE		
	Right (Shrouded)	Left (OEM Configuration)	ΔT	Right (Shrouded)	Left (OEM Configuration)	ΔT
INITIAL BURNISH (NO THERMAL CONTROL AIDS)*						
After 20 Stops	400	150	250	255	150	150
After 40 Stops	340	120	220	200	110	90
After 60 Stops	360	160	200	245	150	95
RERUN BURNISH (WITH THERMAL CONTROL AIDS)**						
After 10 Stops	280	150	130	205	150	75
After 40 Stops	310	150	160	245	165	80
After 60 Stops	265	150	115	215	165	50
After 80 Stops***	200	130	70	160	135	35
After 100 Stops	280	165	115	220	170	50
After 160 Stops	300	170	130	190	130	70

*Test stopped because of failure of Mk II rear drum seal.

**Thermal control aids on front wheel plus Mk III rear drum seal.

***Start of second day.

Table 9-8 - Brake Temperatures During Detroit Traffic Circuits
(Vehicle Test 2 - A.B. Baseline)

Location on Traffic Route	Time of Day (July 20, 1972)	Ambient Temp. °F	Front Disc Brake			Rear Drum Brake		
			Right (Shrouded)	Left (Normal)	ΔT	Right (Shrouded)	Left (Normal)	ΔT
12 Mile and Woodward	6:25 am	75	180	130	50	120	120	0
Michigan and Third	6:50	78	260	140	120	150	140	10
Adams and Woodward	6:59	78	260	150	110	140	140	0
Adams and Woodward	7:13	79	270	150	120	150	150	0
12 Mile and Woodward	7:54	79	270	150	120	150	150	0
12 Mile and Woodward	7:54 am	79	270	150	120	150	150	0
Michigan and Third	8:37	80	300	160	140	170	160	10
Adams and Woodward	8:52	82	300	160	140	180	160	20
Adams and Woodward	9:08	82	280	150	140	180	160	20
12 Mile and Woodward	9:48	84	330	190	140	190	160	30
12 Mile and Woodward	9:48 am	84	330	190	140	190	160	80
Michigan and Third	10:25	85	310	170	140	200	170	30
Adams and Woodward	10:38	85	300	170	130	190	140	20
Adams and Woodward	10:49	87	280	160	120	180	170	10
12 Mile and Woodward	11:34	85	310	160	150	190	160	30
12 Mile and Woodward	1:00 pm	90	310	210	100	160	160	0
Michigan and Third	1:42	91	320	180	140	210	180	30
Adams and Woodward	1:59	91	310	180	130	210	180	30
Adams and Woodward	2:17	91	310	170	140	200	170	30
12 Mile and Woodward	2:50	91	300	160	140	170	150	20
	Range (°F)		260-330	150-210	110-140	140-210	140-180	10-30

July day with ambient temperatures up to 91°F. The Δt between the front brakes remained between 110 and 140°F while that for the rear drum brakes remained between 10 and 30°F.

The temperature trends discussed here were typical for all three vehicle tests.

9.2.2.2 Heavy-Duty Fade Stops

During the Detroit Traffic Test, a series of stops from 40 mph, in rapid succession, every two blocks caused all four brakes to rise in temperature faster than normal. The shrouded brakes would then cool slower than the normal brakes during subsequent running. Consequently, it was anticipated that during the fade tests it would be necessary to program the right front disc brake according to the known temperature versus stop number for the same friction materials previously run on an inertia dynamometer and on a normal test vehicle.

The dynamometer and normal vehicle test baseline results are given in Figure 9-1. Two different dynamometer tests are included. The data for the shrouded right front disc brake and the normal left front disc brake are superimposed on the baseline results. After the 7th stop, the time increment was increased for the vehicle test to prevent the right front disc brake from overheating the lining and creating an abnormal situation. The left brake showed a slight temperature reduction during this increased interval. The right front brake was thus held to the illustrated time-versus-stop curve by increasing the interval as necessary. A temperature of 525°F was recorded as the temperature before the 10th stop. Temperature excursions after the last two stops were higher than 540°F. The recovery stops demonstrated the rate at which the brakes returned to their normal operating temperatures.

The data for the rear drum brakes are also shown in Figure 9-1. The shrouded rear drum brake followed the baseline curve closely. The left rear drum brake showed a slight temperature reduction with the increase in interval. During the recovery stops, both rear brakes followed the baseline cooling curve closer than the corresponding disc brakes followed their baseline cooling curve.

Figure 9-2 shows the corresponding data for the 15-Stop Fade schedule. Baseline data for two inertia dynamometer tests are also plotted on the graph. During the vehicle test, the shrouded right front disc brake began to heat more rapidly than expected (based on the 10-stop fade experience) and the increased interval for cooling between stops was first necessary after the 5th stop. Additional increased intervals were then necessary after each succeeding stop. Consequently, the left front disc brake never did increase above 300°F. A temperature of 575°F was recorded as the temperature before the 15th stop. Temperature excursions after the last 6 stops were higher than 600°F.

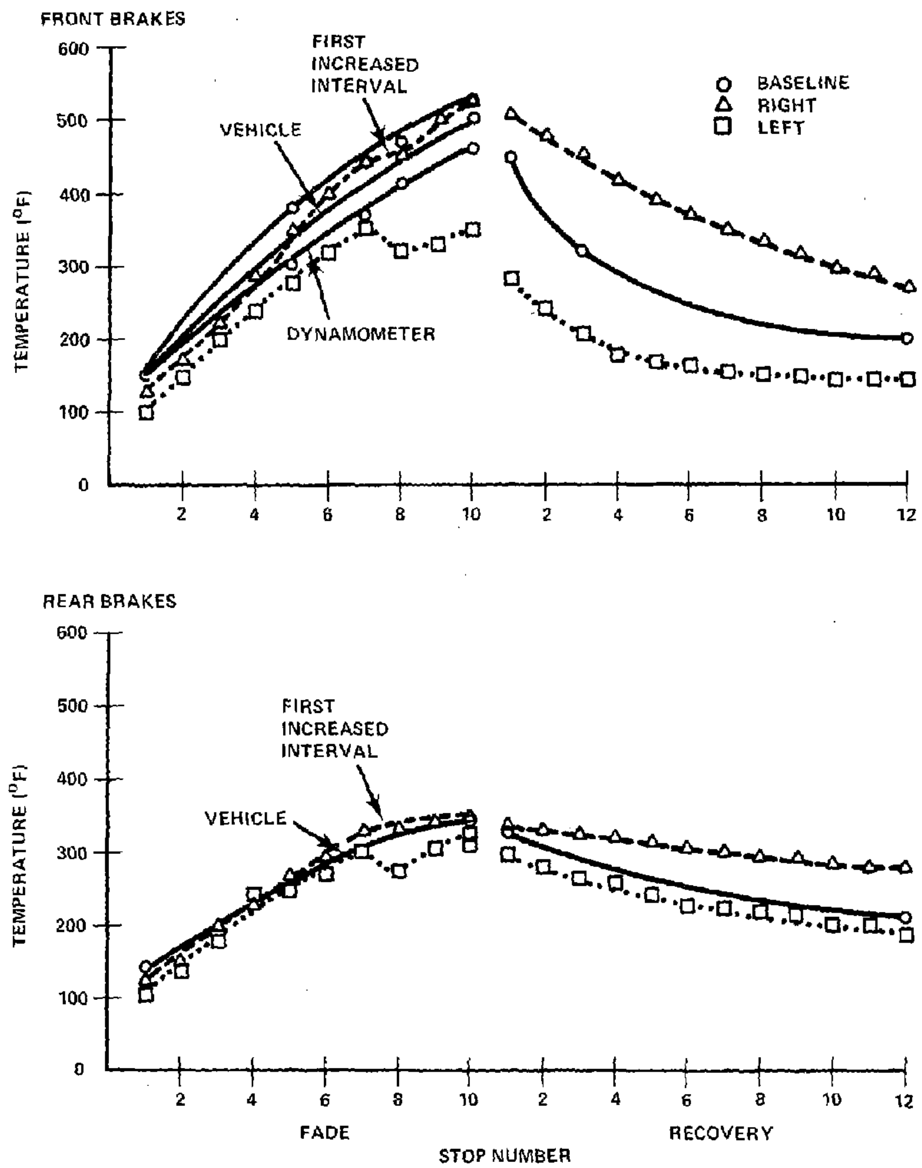
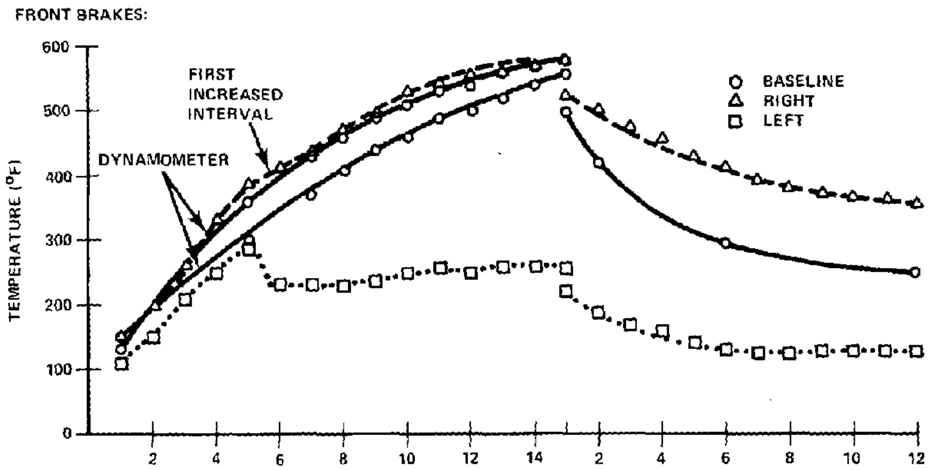


Figure 9-1 - Brake Temperature Data - Vehicle Test 1, 10-Stop Fade



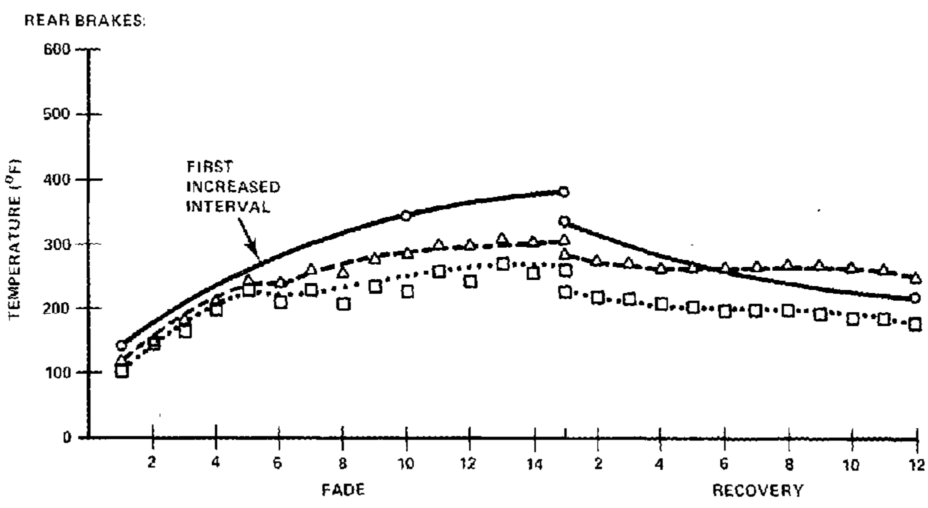


Figure 9-2 - Brake Temperature Data - Vehicle Test 1, 15-Stop Fade

The long time period at which the brakes were above 500°F produced an additional effect within the shrouded brake. The heat generated at the rotor/pad interfaces was retained within the shroud and caused the brake fluid within the right front caliper to heat. The resultant boiling of fluid produced a "loss of brake pedal" for the 14th and 15th stops; the brakes bottomed out, and pumping the brakes did not restore adequate line pressure to maintain the planned deceleration.

The recovery data illustrate the rate at which the shrouded brakes recovered from the high-temperature testing. The fluid boil (soft pedal) persisted through the first eight recovery stops until the indicated lining temperature of the shrouded brake fell below 400°F. This behavior demonstrates the effectiveness of air cooling in keeping brake temperature low on normal unshrouded brakes.

The data for the drum brakes are also illustrated in Figure 9-2. The increased interval early in the test sequence held the temperatures lower than for the baseline data.

The temperature trends discussed for the fade schedules were typical for all three vehicle tests.

9.2.3 Collection Efficiencies

9.2.3.1 Recovery of Brake Particulate Emission

The weights of brake particulate wear debris collected during vehicle tests 1, 2, and 3 are given in Tables 9-9, 9-10, and 9-11, respectively.

For the right front disc brake, the surface sample has the largest weight of the three samples taken. The sump and airborne samples are comparable in weight. For the left front brake, the sump sample was comparable in weight to the right front brake. Moreover the total weight of the samples taken from the left front brake of vehicle tests 1 and 2 were comparable when added for each schedule to arrive at a total weight for the entire vehicle test. On the other hand, the cumulative sample taken for all of the vehicle test 3 was significantly less.

For the right rear drum brake, the surfaces sample has the largest weight of the three samples taken. The sump and the airborne samples are comparable in weight. In some instances, the results for the sump value were reported negative. This occurred because of the 80 percent return of material to the sump from each preceding schedule. No negative values occurred during the normal driving up to the end of the Detroit Traffic Test schedule. During the more severe fade tests, some of the 80 percent return was redistributed to the surfaces samples. The overall wear debris from each wheel did, however, have a positive weight gain.

Table 9-9 - Weights of Brake Particulate Wear Debris Collected (Vehicle Test 1) (gm)

Schedule	Collector	Front Brakes		Rear Brakes	
		Right (Shrouded)	Left (Normal)	Right (Shrouded)	Left (Normal)
Burnish	Sump Surfaces Airborne	0.142 0.412 0.061	0.116* 0.029 -	0.144 1.170 0.046	0.220 0.394 -
A.B. Baseline	Sump Surfaces Airborne	0.083 0.644 0.130	0.128 0.055 -	0.185 0.590 0.049	0.208 0.205 -
Detroit Traffic	Sump Surfaces Airborne	0.201 2.010 0.237	0.458 0.109 -	0.436 4.052 0.285	1.654 0.878 -
10 Stop Fade	Sump Surfaces Airborne	0.580 1.212 0.013	0.244 0.076 -	-0.335 0.371 0.017	1.120 0.275 -
A.F. Baseline	Sump Surfaces Airborne	0.191 1.764 0.259	0.153 0.030 -	0.060 0.652 0.030	-0.516 1.543 -
15 Stop Fade	Sump Surfaces Airborne	0.616 5.943 0.120	0.150 0.027 -	-0.046 0.100 0.004	-0.330 0.169 -
Final Baseline	Sump Surfaces Airborne	0.154 2.011 0.375	0.138 0.083 -	0.097 0.440 0.003	0.017 0.448 -
Totals	Sump Surfaces Airborne	0.967 13.996 1.195	1.387 0.409 -	0.541 7.375 0.434	2.373 3.912 -
	Entire Test	17.158	1.796	8.350	6.285

*Estimated from cumulative sample (0.145 gm) taken during this schedule only.

Table 9-10 - Weights of Brake Particulate Wear Debris Collected (Vehicle Test 2) (gm)

Schedule	Collector	Front Brakes		Left Brakes	
		Right (Shrouded)	Left (Normal)	Right (Shrouded)	Left (Normal)
Burnish	Sump Surfaces Airborne	0.109 0.432 0.039	0.122 0.032 -	0.105 0.166 0.004	-0.132 0.157 -
A.B. Baseline	Sump Surfaces Airborne	0.049 0.481 0.015	- - -	0.081 0.596 0.007	0.109 0.166 -
Detroit Traffic	Sump Surfaces Airborne	0.042 2.828 0.106	0.343 0.126 -	1.247 4.159 0.056	0.955 0.769 -
10 Stop Fade	Sump Surfaces Airborne	0.170 1.437 0.023	0.128 0.055 -	-0.217 1.322 0.010	-0.597 0.290 -
A.F. Baseline	Sump Surfaces Airborne	0.098 1.114 0.107	0.084 0.036 -	-0.047 0.749 0.004	-0.255 0.328 -
15 Stop Fade	Sump Surfaces Airborne	0.098 2.205 0.099	0.084 0.049 -	-0.047 0.181 0.008	-0.255 0.360 -
Final Baseline	Sump Surfaces Airborne	0.051 1.193 0.138	0.111 0.141 -	0.260* 1.070* 0.011	0.295 0.172 -
Totals	Sump Surfaces Airborne	0.555 9.690 0.527	0.984 0.439 -	0.941 8.293 0.104	0.637 2.242 -
	Entire Test	10.772	1.423	9.288	2.879

*Value may be in error because of brake fluid in collector during Final Baseline schedule.

Table 9-11 - Weights of Brake Particulate Wear Debris Collected (Vehicle Test 3) (gm)

SCHEDULE	COLLECTOR	FRONT BRAKES		REAR BRAKES	
		RIGHT (SHROUDED)	LEFT (NORMAL)	RIGHT (SHROUDED)	LEFT (NORMAL)
Burnish	Sump Surfaces Airborne	0.121 0.408 0.045	Cumulative Sample	0.319 2.056 0.033	Cumulative Sample
A.B. Baseline	Sump Surfaces Airborne	0.266 1.097 0.138		0.215 1.234 0.052	
Detroit Traffic	Sump Surfaces Airborne	0.208 3.773 0.495		0.379 1.154 0.027	
10 Stop Fade	Sump Surfaces Airborne	0.438 0.515 0.188		0.151 0.248 0.015	
A.F. Baseline	Sump Surfaces Airborne	0.033 1.389 0.328		0.118 0.295 0.050	
15 Stop Fade	Sump Surfaces Airborne	0.391 3.075 0.402		0.088 0.184 0.018	
Final Baseline	Sump Surfaces Airborne	0.105 2.860 0.337		0.246 2.288 0.017	
Totals	Sump Surfaces Airborne	1.562 13.117 1.933	0.182 0.169 -	1.516 7.459 0.212	0.974 1.908 -
	Entire Test	16.612	0.351	9.187	2.882

9.2.3.2 Mass Balance

9.2.3.2.1 Amount of Emissions

The initial weights of the brake friction material and the weight losses per wheel are given in Table 9-12. The weights of the particulates collected (Tables 9-9, 9-10, and 9-11) and the data in Table 9-12 were used to calculate the mass balances given in Tables 9-13, 9-14, and 9-15 (numbers not in parentheses).

The right front brake data ranged from approximately 42 percent recovery in the initial tests to approximately 70 percent in the later tests. The low initial recovery may have been due to excess gassing of the green linings resulting in a lower recovery as particulates. This condition changed as the linings became burnished to a greater extent and the frictional heat-affected layer contained more inorganic content. The recovery for the 10-stop fade of vehicle tests 1 and 3 were low as the debris was "tarry" and the surfaces fraction could be collected only with difficulty. The recovery for the 15-stop fade of vehicle tests 1 and 3 was somewhat low, possibly for the same reason.

The left front brake showed the same basic trends as the right front brake, increasing throughout the vehicle tests where normal driving was carried out. During the two fade tests and after fade and Final Baseline, approximately 2 to 3 times more wear debris remained in the unshrouded brake. This may have been due to the high concentration of wear debris produced, which in turn was scraped into the rivet holes during the braking.

The material recovery totals for the rear brakes show wide variations. The problem, in part, was due to the carryover from test-to-test of the sump debris, 80 percent of which was returned to the brake after each test schedule. The data can be explained partially by examination of the distribution of particulate emissions obtained at each sample location.

9.2.3.2.2 Distribution of Emissions

The data given in parentheses in Tables 9-13, 9-14, and 9-15, represent the percent of total particulates collected - the distribution of the particulate emissions. The bottom portion of Tables 9-13, 9-14, and 9-15, shows the ranges for the distribution into sump, surface, and airborne samples.

The data for the rear brakes fell into fairly narrow ranges for the first three schedules only. From the 10-Stop Fade to the Final Baseline, the data show both negative recoveries and greater than 100 percent recoveries. For both the 10- and 15-Stop Fade schedules of vehicle test 1, the negative recovery figures were not reflected by corresponding increases in the surface or airborne figures. However, the reverse situation prevailed in vehicle test 2 for the 10-Stop Fade and the ensuing A.F. Baseline.

Table 9-12 - Brake Friction Material Initial Weights and Weight Losses (gm)

	Duty	Schedule	Vehicle Test 1				Vehicle Test 2				Vehicle Test 3			
			Front		Rear		Front		Rear		Front		Rear	
			Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left
Weight Losses	Moderate	Burnish	1.48	0.96	3.33	1.35	1.45	0.94	0.66	0.79	1.32	0.62	3.11	3.06
		A. B. Baseline	1.86	1.29	0.92	1.21	1.15	1.11	1.21	1.17	2.81	1.39	1.89	0.80
		Detroit Traffic	5.64	4.17	5.80	4.96	4.11	3.53	5.31	4.16	5.02	5.05	1.83	4.67
		Totals	8.98	6.42	10.05	7.52	6.71	5.58	7.18	6.12	9.15	7.06	6.83	8.53
	Heavy to Abusive	10-Stop Fade	5.72	0.78	0.45	0.67	2.69	1.58	1.01	0.54	4.44	0.82	1.22	1.90
		A. F. Baseline	3.34	1.14	1.02	2.39	2.87	1.28	0.28	0.95	2.11	1.17	0.61	1.34
		15-Stop Fade	11.87	0.50	0.29	0.25	3.62	0.49	0.35	0.55	7.79	0.72	1.20	0.80
		Final Baseline	3.73	1.22	0.49	1.13	1.89	0.68	1.57	0.83	4.14	2.44	1.19	1.45
		Totals	24.66	3.64	2.25	4.44	11.07	4.03	3.21	2.87	18.48	5.15	4.30	5.49
	Cumulative	Total Wear	33.64	10.06	12.30	11.96	17.78	9.61	10.39	8.99	27.63	12.21	11.13	14.02
Initial Weights	As Prepared	Inner	95.8	93.8			106.4	106.1			115.3	113.0		
		Outer	117.4	116.5			105.0	105.6			152.3	160.3		
		Primary			108.1	106.4			104.9	102.4			113.2	113.7
		Secondary			189.6	189.3			181.3	180.2			153.5	167.7
		Totals	213.2	210.3	297.7	295.7	211.4	211.7	286.2	282.6	267.6	273.3	266.7	280.4

Table 9-13 - Material Percent Recovery as Particulate Emissions
(Vehicle Test 1)

SCHEDULE	COLLECTOR	FRONT BRAKES RIGHT (SHROUDED)		FRONT BRAKES LEFT (NORMAL)		REAR BRAKES RIGHT (SHROUDED)		REAR BRAKES LEFT (NORMAL)	
Burnish	Sump	(24)*	10	(81)	9	(10)	4	(36)	16
	Surfaces	(67)	28	(19)	2	(87)	36	(64)	29
	Airborne	(9)	4		-	(3)	1		-
	Total		42		11		41		45
A.B. Baseline	Sump	(11)	5	(71)	10	(22)	20	(51)	17
	Surface	(24)	34	(29)	4	(72)	65	(49)	16
	Airborne	(15)	7		-	(6)	5		-
	Total		45		14		90		33
Detroit Traffic	Sump	(10)	4	(79)	11	(9)	7	(65)	33
	Surfaces	(81)	35	(21)	3	(85)	70	(35)	18
	Airborne	(9)	4		-	(6)	5		-
	Total		43		14		82		51
10 Stop Fade	Sump	(31^-)	10	(76)	31		-75		166
	Surfaces	(63^+)	20+	(24)	10		83		41
	Airborne	(6^-)	2		-		4		-
	Total		32+		41		12		207
A. F. Baseline	Sump	(9)	6	(81)	13	(8)	6		-22
	Surfaces	(79)	52	(19)	3	(88)	64		65
	Airborne	(12)	8		-	(4)	3		-
	Total		66		16		73		43
15 Stop Fade	Sump	(9)	5	(88)	30		-16		-133
	Surfaces	(89)	50	(17)	6		35		68
	Airborne	(2)	1		-		1		-
	Total		56		36		20		-65
Final Baseline	Sump	(6)	4	(61)	11		20		1
	Surfaces	(79)	54	(39)	7		90		40
	Airborne	(15)	10		-		1		-
	Total		68		18		111		41
Ranges	Sump	(6-31)		(61-83)		(8-22)		(36-65)	
	Surfaces	(63-89)		(17-39)		(72-88)		(35-65)	
	Airborne	(2-15)		——		(3-6)		——	

*Numbers in parenthesis are percents of total particulates collected: 10/42 = 24%.

+Not all of the sample was recovered.

Table 9-14 - Material Percent Recovery as Particulate Emissions (Vehicle Test 2)

SCHEDULE	COLLECTOR	FRONT BRAKES RIGHT (SHROUDED)	FRONT BRAKES LEFT (NORMAL)	REAR BRAKES RIGHT (SHROUDED)	REAR BRAKES LEFT (NORMAL)
Burnish	Sump	(20)* 8	(81) 13	(38) 16	-17
	Surfaces	(73) 30	(10) 3	(60) 25	20
	Airborne	(7) 3	-	(2) 1	-
	Total	41	16	42	3
A.B. Baseline	Sump	(7) 4	Not Sampled	(12) 7	(39) 9
	Surface	(71) 41		(86) 49	(61) 14
	Airborne	(22) 13		(2) 1	-
	Total	58		57	23
Detroit Traffic	Sump	(2) 1	(72) 10	(22) 23	(56) 23
	Surfaces	(93) 65	(28) 4	(77) 78	(44) 18
	Airborne	(5) 3	-	(1) 1	-
	Total	69	14	102	41
10 Stop Fade	Sump	(10) 6	(72) 8	-22	-110
	Surfaces	(88) 33	(28) 3	131	54
	Airborne	(2) 1	-	1	-
	Total	60	11	111	-56
A.F. Baseline	Sump	(2) 1	(83) 15	-181	(44) 28
	Surfaces	(89) 39	(17) 3	267	(56) 35
	Airborne	(9) 4	-	1	-
	Total	44	18	87	63
15 Stop Fade	Sump	(5) 3	(63) 17	-13	-46
	Surfaces	(90) 61	(37) 10	52	65
	Airborne	(5) 3	-	2	-
	Total	67	27	41	19
Final Baseline	Sump	(4) 3	16	Brake Fluid in Linings	(63) 36
	Surfaces	(86) 63	21		(37) 21
	Airborne	(10) 7	-		-
	Total	73	37		57
Ranges	Sump	(2-20)	(63-83)	(12-22)	(39-63)
	Surfaces	(71-93)	(17-37)	(60-86)	(37-61)
	Airborne	(2-22)		(1-2)	

*Numbers in brackets are percents of total particulates collected: 8/41 = 20%

Table 9-15 - Material Percent Recovery as Particulate Emissions
(Vehicle Test 3)

SCHEDULE	COLLECTOR	FRONT BRAKES		REAR BRAKES	
		RIGHT (SHROUDED)	LEFT (NORMAL)	RIGHT (SHROUDED)	LEFT (NORMAL)
Burnish	Sump	(21)* 9	Cumulative Sample	(13) 10	Cumulative Sample
	Surfaces	(72) 31		(83) 66	
	Airborne	(7) 3		(4) 3	
	Total	43		79	
A.B. Baseline	Sump	(19) 10		(9) 7	
	Surfaces	(72) 39		(87) 65	
	Airborne	(9) 5		(4) 3	
	Total	54		75	
Detroit Traffic	Sump	(5) 4		(25) 21	
	Surfaces	(85) 75		(74) 63	
	Airborne	(11) 10		(1) 1	
	Total	89		85	
10 Stop Fade	Sump	(38) 10		(36) 12	
	Surfaces	(46) 12		(61) 20	
	Airborne	(16) 4		(3) 1	
	Total	26		33	
A.F. Baseline	Sump	(2) 2		(25) 19	
	Surfaces	(79) 66		(64) 48	
	Airborne	(19) 16		(11) 8	
	Total	84		75	
15 Stop Fade	Sump	(20) 10		(32) 7	
	Surfaces	(70) 34		(64) 14	
	Airborne	(10) 5		(4) 1	
	Total	49		22	
Final Baseline	Sump	(4) 3	(52) 1.5	H_2O in Linings	(34) 9
	Surfaces	(86) 69	(48) 1.4		(66) 17
	Airborne	(10) 8	-		-
	Total	80	3		26
Ranges	Sump	(2-38)		(9-36)	
	Surfaces	(46-86)		(61-87)	
	Airborne	(7-19)		(1-11)	

*Numbers in brackets are percents of total particulates collected.

The ranges for the sump, surfaces, and airborne samples given at the bottom of all three tables agreed rather well for all brakes irregardless of the brake friction materials used or the rotor conditions prior to the start of the test.

9.3 PERCENT ASBESTOS CONTENTS

9.3.1 Program Results

The microscopy results were converted by the computer into the asbestos emissions results summarized in Tables 9-16, 9-17, and 9-18.

For vehicle test 1, the range of asbestos contents in brake emissions varies from a high of 1.65 percent down to a low of 0.05 percent. Of the 47 analyses reported, only two were above 1.00 percent. The overall average was 0.38 percent.

For vehicle test 2, the range of asbestos contents in brake emissions varies from a high of 1.42 percent down to a low of 0.03 percent. Of the 43 analyses reported, only one was above 1.09 percent, and only three were in the range 0.50 to 0.96 percent; all others were less than 0.50 percent. The overall average was 0.25 percent.

For vehicle test 3, the range of asbestos content in brake emissions varies from a high of 0.51 percent down to a low of 0.003 percent. Of the analyses reported, three were in the range 0.20 to 0.51 percent; all others were less than 0.20 percent. The overall average was 0.07 percent.

For all three vehicle tests, the overall average of asbestos content in the brake emissions was 0.23 percent. The following trends were noteworthy:

- The right front disc brake yielded higher asbestos contents than the right rear drum brake (for two of the three vehicle tests):

Vehicle Test	R.F. Disc (%)	R.R. Drum (%)
1	0.45	0.30
2	0.26	0.24
3	0.07	0.07

- In general, the airborne samples contained a lower asbestos weight percent than the corresponding sump and surfaces samples.
- In general, the asbestos weight percent in brake emissions was higher when the materials were new; the asbestos content decreases with brake use.
- For all vehicle tests, the asbestos weight percent increased only slightly for the severely burnished brakes during the fade tests.

Table 9-16 - Summary of Asbestos Analytical Results (Vehicle Test 1)
(Weight Percent)

Schedule	Collector	Front Brakes		Rear Brakes	
		Right (Shrouded)	Left (Normal)	Right (Shrouded)	Left (Normal)
Burnish	Sump	0.813	Not** Analyzed	-	Not Analyzed
	Surfaces	0.398		0.865	
	Airborne	0.144		0.349	
		(0.452)*		(0.607)	
A.B. Baseline	Sump	1.650		0.179	
	Surfaces	0.472		0.415	
	Airborne	0.290		0.493	
		(0.804)		(0.362)	
Detroit Traffic	Sump	0.247		0.129	0.991
	Surfaces	0.137		0.373	0.265
	Airborne	0.052		0.092	-
		(0.145)		(0.198)	
10-Stop Fade	Sump	0.463		0.280	0.275
	Surfaces	0.162		0.071	0.416
	Airborne	0.154		0.132	
		(0.260)		(0.161)	
A.F. Baseline	Sump	0.656		0.419	Not Analyzed
	Surfaces	0.507		0.242	
	Airborne	0.134		0.079	
		(0.432)		(0.247)	
15-Stop Fade	Sump	0.602		0.071	0.439
	Surfaces	1.548		0.257	0.472
	Airborne	0.175		0.222	-
		(0.775)		(0.183	
Final Baseline	Sump	0.435		0.585	Not Analyzed
	Surfaces	0.290		0.324	
	Airborne	0.167		0.145	
		(0.297)		(0.351)	
	Average	0.452	Average	0.301	

*Average value for wheel where collection took place.
**Not Analyzed - indicates that analysis was not required.

Table 9-17 - Summary of Asbestos Analytical Results (Vehicle Test 2)
(Weight Percent)

SCHEDULE	COLLECTOR	FRONT BRAKES		REAR BRAKES	
		RIGHT (SHROUDED)	LEFT (NORMAL)	RIGHT (SHROUDED)	LEFT (NORMAL)
Burnish	Sump Surfaces Airborne	0.402 0.968 0.186 (0.515)*	Not Analyzed	0.484 1.416 0.087 (0.636)	Not Analyzed
A.B. Baseline	Sump Surfaces Airborne	0.236 0.311 0.211 (0.253)		0.268 0.098 0.344 (0.237)	
Detroit Traffic	Sump Surfaces Airborne	0.304 0.548 0.234 (0.362)		0.249 0.113 0.115 (0.159)	
10-Stop Fade	Sump Surfaces Airborne	0.244 0.261 0.107 (0.260)		0.199 0.619 0.194 (0.185)	
A.F. Baseline	Sump Surfaces Airborne	0.443 0.173 0.165 (0.260)		0.138 0.237 0.180 (0.185)	
15-Stop Fade	Sump Surfaces Airborne	0.119 0.193 0.095 (0.136)		0.065 0.136 0.048 (0.083)	
Final Baseline	Sump Surfaces Airborne	0.117 0.071 0.032 (0.073)		0.058 0.067 (0.063)	
	Average	0.258	Average	0.243	

*Average value for wheel where collective took place.

Table 9-18 - Summary of Asbestos Analytical Results (Vehicle Test 3) (Weight Percent)

SCHEDULE	COLLECTOR	FRONT BRAKES		REAR BRAKES	
		RIGHT (SHROUDED)	LEFT (NORMAL)	RIGHT (SHROUDED)	LEFT (NORMAL)
Burnish	Sump Surfaces Airborne	0.218 0.101 0.099 (0.109)*	Cumulative Sample	0.063 0.046 0.060 (0.056)	Cumulative Sample
A.B. Baseline	Sump Surfaces Airborne	0.106 0.024 0.125 (0.085)		0.063 0.056 0.044 (0.054)	
Detroit Traffic	Sump Surfaces Airborne	0.018 0.013 0.025 (0.019)		0.046 0.057 0.037 (0.047)	
10-Stop Fade	Sump Surfaces Airborne	0.045 0.041 0.055 (0.047)		0.102 0.055 0.014 (0.057)	
A.F. Baseline	Sump Surfaces Airborne	0.158 0.073 0.047 (0.093)		0.034 0.022 0.003 (0.019)	
15-Stop Fade	Sump Surfaces Airborne	0.109 0.047 0.035 (0.064)		0.065 0.025 0.014 (0.035)	
Final Baseline	Sump Surfaces Airborne	0.089 0.087 0.037 (0.071)	Not Analyzed	0.512 0.237 0.035 (0.261)	0.026 0.031 -
	Average	0.070	Average	0.074	

*Average value for wheel where collection took place.

- The data for vehicle test 2 showed slightly lower emissions than for vehicle test 1 (Test 2 started with smoother used rotor surfaces.)

9.3.2 Battelle Analyses

The contractual requirements for the asbestos particle size distribution in addition to the asbestos content placed undue burden on the accuracy of the asbestos content calculation. To provide a systematic independent check on the asbestos emissions analyses, the EPA Project Officer arranged a second contract for Battelle Columbus Laboratories to analyze 24 samples generated by the program. The analytical method used by Battelle was developed for EPA under a separate contract. The method is outlined in Appendix H.

The Battelle results are given in Appendix H. Mr. Carl Melton was the Battelle Technical Contact.

9.3.3 Johns-Manville Analyses

During the course of the program, Johns-Manville volunteered to analyze three samples from the program using an analytical procedure which they had developed for the determination of low asbestos contents in brake wear debris. Drs. Sidney Spiel and James Leineweber conducted these tests. The results are given in Appendix H.

9.3.4 Comparison of Asbestos Analytical Results

Table 9-19 gives the comparative data for the asbestos analytical results obtained by the program, Battelle, and Johns-Manville. The three Johns-Manville results agreed with the Battelle data as expected.

In 19 of the 24 analyses, the program results were higher for asbestos percent than the corresponding data from Battelle. The five Battelle results that were larger than the corresponding program results were larger by the following factors: 7.5, 2.6, 2.1, 2.1, and 1.2. There were three program results larger than the corresponding Battelle results by a factor of less than 1.5. Of the remaining 16 comparative sets of data, two program results were greater by a factor in the range 1.5 to 2.5, eight program results were greater by a factor in the range 2.5 to 10, and six program results were greater by a factor in the range 10 to 100. The program average was 0.25 percent, while the Battelle average was 0.17 percent, or 68 percent of the Program average.

The program data were expected to be higher for the following reasons:

- All fibers found were assumed to be cylinders of projected diameter and length as indicated by microscopy. A fiber with an elliptical cross section will actually be smaller in volume than that reported.
- All fibers found were assumed to be 100 percent asbestos. Partially degraded asbestos fibers are similar to asbestos and were counted. This is especially true for the larger fibers.

Table 9-19 - Comparison of Analytical Results for Asbestos

			Front Disc Brakes			Rear Drum Brakes			Clutch	
	Schedule	Collector	Program	JM	Battelle	Program	JM	Battelle	Program	Battelle
Vehicle Test 1	Detroit Traffic	Sump	0.247	-	0.21	0.129	-	0.025	-	-
		Surfaces	0.137	0.005	0.011	0.373	0.002	0.006	-	-
		Airborne	0.052	-	0.001	0.092	0.006	0.001	0.291	0.007
	10-Stop Fade	Sump	0.463	-	1.22	0.280	-	0.22	-	-
		Surfaces	-	-	-	-	-	-	-	-
		Airborne	0.254	-	0.31	0.132	-	0.007	-	-
Vehicle Test 2	Burnish	Sump	0.402	-	0.28	0.484	-	0.10	-	-
		Surfaces	-	-	-	1.416	-	0.38	-	-
		Airborne	0.186	-	0.10	-	-	-	-	-
	Detroit Traffic	Sump	0.304	-	0.62	0.249	-	0.057	-	-
		Surfaces	-	-	-	0.113	-	0.061	-	-
		Airborne	0.234	-	0.006	0.115	-	0.015	-	-
Vehicle Test 3	Detroit Traffic	Sump	0.018	-	0.135	0.046	-	0.010	-	-
		Surfaces	-	-	-	-	-	-	-	-
		Airborne	0.025	-	0.016	0.037	-	0.044	-	-
		Averages	0.204	-	0.265	0.289	-	0.077	-	-

Program Average: 0.25
Battelle Average: 0.17
Ratio: Battelle/Program = 0.69

- Other analytical techniques rely on reducing all asbestos to its fibril nature where dimensions and structure are well characterized. At the same time, all olivine and partially degraded asbestos are mechanically reduced to a nonfibrous nature so that only the stronger asbestos fibrils that remain are counted.

9.4 ASBESTOS EMISSIONS FACTORS

To compare the generation of asbestos emissions properly on a mass-weighted basis, it was found necessary to calculate the asbestos emissions factors in weight and in weight per mile. These weights of asbestos emissions were obtained by multiplying the weight of brake wear debris generated (Tables 9-9, 9-10, or 9-11) by the appropriate asbestos percent determined for that weight of debris produced (Tables 9-16, 9-17, or 9-18). These data are expressed in mg in Tables 9-20, 9-21, and 9-22.

Example:

$$\left.\begin{array}{l}\text{Vehicle Test 2}\\ \text{Burnish}\\ \text{Right Front Brake}\\ \text{Sump}\end{array}\right\}\quad \text{Sample}$$

From Table 9-10:

Weight of sample collected: 0.109 gm

From Table 9-17:

Asbestos weight percent: 0.402

Data given in Table 9-21:

$$0.10\ \text{gm} \times 1000\ \frac{\text{mg}}{\text{gm}} \times 0.00402 = 0.438\ \text{mg}$$

Using the mileages reported in Table 9-4, the asbestos emission in μg per mile are given in Tables 9-23, 9-24, and 9-25.

Example:

Sample same as that used in above example.

From Table 9-21:

Asbestos weight produced for entire test: 0.438 mg

From Table 9-4:

Mileage for Burnish Sequence of vehicle test 2: 127 miles

Data given in Table 9-24:

$$0.438\ \text{mg} \times 1000\ \frac{\mu\text{g}}{\text{mg}} \div 127\ \text{miles} = 3.45\ \mu\text{g/mile}.$$

Table 9-20 – Weight of Asbestos Generated During Braking (Vehicle Test 1) (mg)

SCHEDULE	COLLECTOR	FRONT BRAKES		REAR BRAKES	
		RIGHT (SHROUDED)	LEFT (NORMAL)	RIGHT (SHROUDED)	LEFT (NORMAL)
Burnish	Sump	1.160	Not Analyzed	N/A	Not Analyzed
	Surfaces	1.640		10.121	
	Airborne	0.088		0.161	
	Total	2.888		10.282	
A.B. Baseline	Sump	0.137		0.331	
	Surfaces	0.340		2.449	
	Airborne	0.377		0.242	
	Total	0.854		3.022	
Detroit Traffic	Sump	0.497		0.562	16.350
	Surfaces	2.754		15.114	2.315
	Airborne	0.123		0.262	
	Total	3.374		15.938	18.665
10-Stop Fade	Sump	2.685		–	3.180
	Surfaces	1.963		1.039	1.143
	Airborne	0.080		0.022	–
	Total	4.728		1.061	4.323
A.F. Baseline	Sump	1.253		0.251	Not Analyzed
	Surfaces	8.943		1.578	
	Airborne	0.347		0.024	
	Total	10.543		1.853	
15-Stop Fade	Sump	3.708		–	–
	Surfaces	91.998		0.257	0.798
	Airborne	0.210		0.009	–
	Total	95.916		0.266	0.798
Final Baseline	Sump	0.670		0.567	Not Analyzed
	Surfaces	8.748		1.426	
	Airborne	0.626		0.004	
	Total	10.044		1.997	

Table 9-21 - Weight of Asbestos Generated During Braking
(Vehicle Test 2) (mg)

SCHEDULE	COLLECTOR	FRONT BRAKES		REAR BRAKES	
		RIGHT (SHROUDED)	LEFT (NORMAL)	RIGHT (SHROUDED)	LEFT (NORMAL)
Burnish	Sump	0.438	Not Analyzed	0.508	Not Analyzed
	Surfaces	4.190		2.350	
	Airborne	0.026		0.035	
	Total	4.654		2.893	
A.B. Baseline	Sump	0.116		0.217	
	Surfaces	1.495		0.584	
	Airborne	0.032		0.028	
	Total	1.643		0.829	
Detroit Traffic	Sump	0.127		3.108	
	Surfaces	15.620		4.705	
	Airborne	2.510		0.064	
	Total	18.237		7.877	
10-Stop Fade	Sump	0.415		-0.430	
	Surfaces	3.755		8.190	
	Airborne	0.024		0.019	
	Total	4.194		7.779	
A.F. Baseline	Sump	0.160		-0.672	
	Surfaces	1.932		1.775	
	Airborne	0.177		0.007	
	Total	2.269		1.110	
15-Stop Fade	Sump	0.117		-0.031	
	Surfaces	4.250		0.246	
	Airborne	0.094		0.004	
	Total	4.461		0.229	
Final Baseline	Sump	0.051		0.847	
	Surfaces	0.851			
	Airborne	0.044		0.074	
	Total	0.946		0.921	

Table 9-22 - Weight of Asbestos Generated During Braking (Vehicle Test 3) (mg)

SCHEDULE	COLLECTOR	FRONT BRAKES RIGHT (SHROUDED)	FRONT BRAKES LEFT (NORMAL)	REAR BRAKES RIGHT (SHROUDED)	REAR BRAKES LEFT (NORMAL)
Burnish	Sump	0.264	Cumulative Sample	0.201	Cumulative Sample
	Surfaces	0.412		0.946	
	Airborne	0.045		0.020	
	Total	0.721		1.167	
A.B. Baseline	Sump	0.282		0.135	
	Surfaces	0.263		0.691	
	Airborne	0.173		0.023	
	Total	0.718		0.849	
Detroit Traffic	Sump	0.037		0.174	
	Surfaces	0.490		0.658	
	Airborne	0.124		0.010	
	Total	0.651		0.842	
10-Stop Fade	Sump	0.197		0.154	
	Surfaces	0.211		0.136	
	Airborne	0.103		0.002	
	Total	0.511		0.292	
A.F. Baseline	Sump	0.052		0.040	
	Surfaces	1.014		0.065	
	Airborne	0.154		0.002	
	Total	1.220		0.107	
15-Stop Fade	Sump	0.426		0.057	
	Surfaces	1.445		0.046	
	Airborne	0.141		0.003	
	Total	2.012		0.106	
Final Baseline	Sump	0.093	Not Analyzed	1.260	0.253
	Surfaces	2.488		5.422	0.591
	Airborne	0.125		0.006	-
	Total	2.706		6.688	0.844

Table 9-23 - Weight of Asbestos Generated During Braking (Vehicle Test 1) (μg/mile)

Schedule	Collector	Front Brakes		Rear Brakes	
		Right (Shrouded)	Left (Normal)	Right (Shrouded)	Left (Normal)
Burnish	Sump	6.77	Not Analyzed	N/A	Not Analyzed
	Surfaces	9.42		58.11	
	Airborne	0.51		0.92	
	Total	16.70		59.09	
A.B. Baseline	Sump	0.04		1.01	
	Surfaces	1.04		7.47	
	Airborne	1.15		0.74	
	Total	2.23		9.22	
Detroit Traffic	Sump	0.35		0.39	13.52
	Surfaces	1.91		10.50	1.61
	Airborne	0.09		0.18	-
	Total	2.35		11.07	14.13
10-Stop Fade	Sump	57.13		-	67.85
	Surfaces	41.77		22.11	24.35
	Airborne	1.70		0.47	-
	Total	100.60		22.58	92.20
A.F. Baseline	Sump	3.52		0.71	Not Analyzed
	Surfaces	25.12		4.43	
	Airborne	0.97		0.07	
	Total	29.61		5.21	
15-Stop Fade	Sump	78.89		-	
	Surfaces	1957.40		5.47	
	Airborne	4.47		0.19	
	Total	2040.76		5.66	
Final Baseline	Sump	1.90		1.61	
	Surfaces	24.85		4.05	
	Airborne	1.78		0.01	
	Total	28.53		5.67	

Table 9-24 - Weight of Asbestos Generated During Braking (Vehicle Test 2) (μg/mile)

SCHEDULE	COLLECTOR	FRONT BRAKES RIGHT (SHROUDED)	FRONT BRAKES LEFT (NORMAL)	REAR BRAKES RIGHT (SHROUDED)	REAR BRAKES LEFT (NORMAL)
Burnish	Sump	3.45	Not Analyzed	4.63	Not Analyzed
	Surfaces	32.70		18.52	
	Airborne	0.20		0.28	
	Total	36.35		23.43	
A.B. Baseline	Sump	0.33		0.62	
	Surfaces	4.29		1.68	
	Airborne	0.09		0.08	
	Total	4.71		2.38	
Detroit Traffic	Sump	0.09		2.17	
	Surfaces	10.92		3.29	
	Airborne	1.74		0.04	
	Total	12.75		5.50	
10-Stop Fade	Sump	7.83		- 8.22	
	Surfaces	70.85		154.50	
	Airborne	0.45		0.36	
	Total	79.13		146.64	
A.F. Baseline	Sump	0.47		-1.98	
	Surfaces	5.70		5.24	
	Airborne	0.52		0.02	
	Total	6.69		3.28	
15-Stop Fade	Sump	1.48		-0.39	
	Surfaces	53.85		3.11	
	Airborne	1.19		0.05	
	Total	56.52		2.77	
Final Baseline	Sump	0.16		2.60	
	Surfaces	2.61			
	Airborne	0.14		0.23	
	Total	2.91		2.83	

Table 9-25 - Weight of Asbestos Generated During Braking (Vehicle Test 3) (μg/mile)

SCHEDULE	COLLECTOR	FRONT BRAKES RIGHT (SHROUDED)	FRONT BRAKES LEFT (NORMAL)	REAR BRAKES RIGHT (SHROUDED)	REAR BRAKES LEFT (NORMAL)
Burnish	Sump Surfaces Airborne Total	2.64 4.12 0.45 7.21	Cumulative Sample	2.01 9.46 0.20 11.67	Cumulative Sample
A.B. Baseline	Sump Surfaces Airborne Total	0.77 0.72 0.47 1.96		0.04 1.88 0.06 1.98	
Detroit Traffic	Sump Surfaces Airborne Total	0.03 0.36 0.09 0.48		0.13 0.49 0.01 0.63	
10-stop Fade	Sump Surfaces Airborne Total	3.40 3.64 1.78 8.82		2.66 2.34 0.03 5.03	
A.F. Baseline	Sump Surfaces Airborne Total	0.15 2.94 0.44 3.51		0.12 0.19 0.01 0.32	
15-Stop Fade	Sump Surfaces Airborne Total	7.22 24.49 3.20 34.91		0.97 0.78 0.05 1.80	
Final Baseline	Sump Surfaces Airborne Total	0.27 7.25 0.36 7.88	Not Analyzed	3.67 15.81 0.02 19.50	0.10 0.22 -

The data for the clutch emissions are given in Table 9-26. During vehicle test 1 and the early stages of vehicle test 2, it was decided to combine the very small airborne samples collected as indicated in Table 9-19. The treatment of the data to arrive at the asbestos emissions in μg/mile was similar to that for the brake emissions given earlier.

9.5 ASBESTOS EMISSIONS TRENDS

9.5.1 New versus Burnished Materials

The comparison of the Burnish, A.B. Baseline, and Detroit Traffic Test overall asbestos emissions data is given in Table 9-27. Both the right front disc brake and the right rear drum brake show that the asbestos emissions generated during the Burnish schedule are higher for the new friction materials. Asbestos emissions decrease for slightly used materials during the A.B. Baseline schedule. The asbestos emissions increase slightly with increased use as shown with the Detroit Traffic test.

The rear drum brake data showed two effects brought out by the vehicle test scheduling and material selections:

- The data above indicate that the Detroit Traffic asbestos emissions are higher than for the A.B. Baseline. This effect is probably due to the extent of conditioning of the lining prior to each test. The Burnish duty is slightly heavier than the A.B. Baseline duty and this may be responsible for the differences between the A.B. Baseline and the Detroit Traffic results, even though both latter tests are identical in duty.
- Vehicle test 2 used the same linings as vehicle test 1. The Burnish, A.B. Baseline, and Detroit Traffic schedules showed lower asbestos emissions than vehicle test 1. The data demonstrate that asbestos emissions decrease with increased lining life.

The amount of clutch airborne wear debris collected for vehicle test 2 was less than for vehicle test 1. The progression through vehicle test 3 would have continued, except for the fact that several severe clutch applications and clutch slippages were made to increase the amount of debris to simulate generation of emissions under more severe conditions. In spite of this practice, the asbestos percent of the debris and the airborne asbestos emissions content for the clutch samples decreased with use as shown in Figure 9-3.

9.5.2 Disc Versus Drum Brake Materials

The data given in Table 9-27 also indicate the following trends:

- For all moderate-duty schedules, the drum brakes produced more total emissions than the disc brake.

Table 9-26 - Summary of Clutch Asbestos Emissions

SAMPLE	VEHICLE TEST	SCHEDULE	WEAR DEBRIS WEIGHT (gm)	ASBESTOS WEIGHT PERCENT	ASBESTOS (Mg)	ASBESTOS (ug/mile)
AIRBORNE	1	Burnish	0.0005	N/A		
		A.B. Baseline	0.0042	N/A		
		Detroit Traffic	0.0097	0.291	0.028	0.019
		10-Stop Fade	0.0001			
		A.F. Baseline	0.0009	0.493	0.026	0.032
		15-Stop Fade	0.0003			
		Final Baseline	0.0040			(0.023)
	2	Burnish	0.0004	N/A		
		Cumulative (A.B.Baseline To Final Baseline)	0.0058	0.136	0.008	0.003
	3	Cumulative (Burnish to Final Baseline)	0.0126	0.035	0.004	0.001
SURFACES	Cumulative for all 3 Vehicle Tests		1.9519	0.099	1.930	0.239
SUMP	Cumulative for all 3 Vehicle Tests		14.8472	0.047	6.990	0.864

Table 9-27 - Comparison of Asbestos Emissions from New and Burnished Materials

Location	Vehicle Test	Burnish (ug/mile)	A.B. Baseline (ug/mile)	Detroit Traffic (Mg/mile)	$\frac{\text{Burnish}}{\text{A.B. Baseline}}$	$\frac{\text{Burnish}}{\frac{\text{A.B.B. + D.T.}}{2}}$
RIGHT FRONT DISC BRAKE	1	16.70	2.23	2.35	7.5	7.3
	2	36.35	4.71	12.75	7.7	5.3
	3	7.21	1.96	0.48	3.7	9.2
	Totals	60.26	8.90	15.58	Average: 6.3	Average: 7.3
RIGHT REAR DRUM BRAKE	1	59.09	9.22	11.07	6.4	5.8
	2	24.43	2.38	5.50	10.3	7.3
	3	11.67	1.98	0.63	5.9	12.2
	Totals	94.19	13.58	17.20	Average: 7.5	Average: 8.8

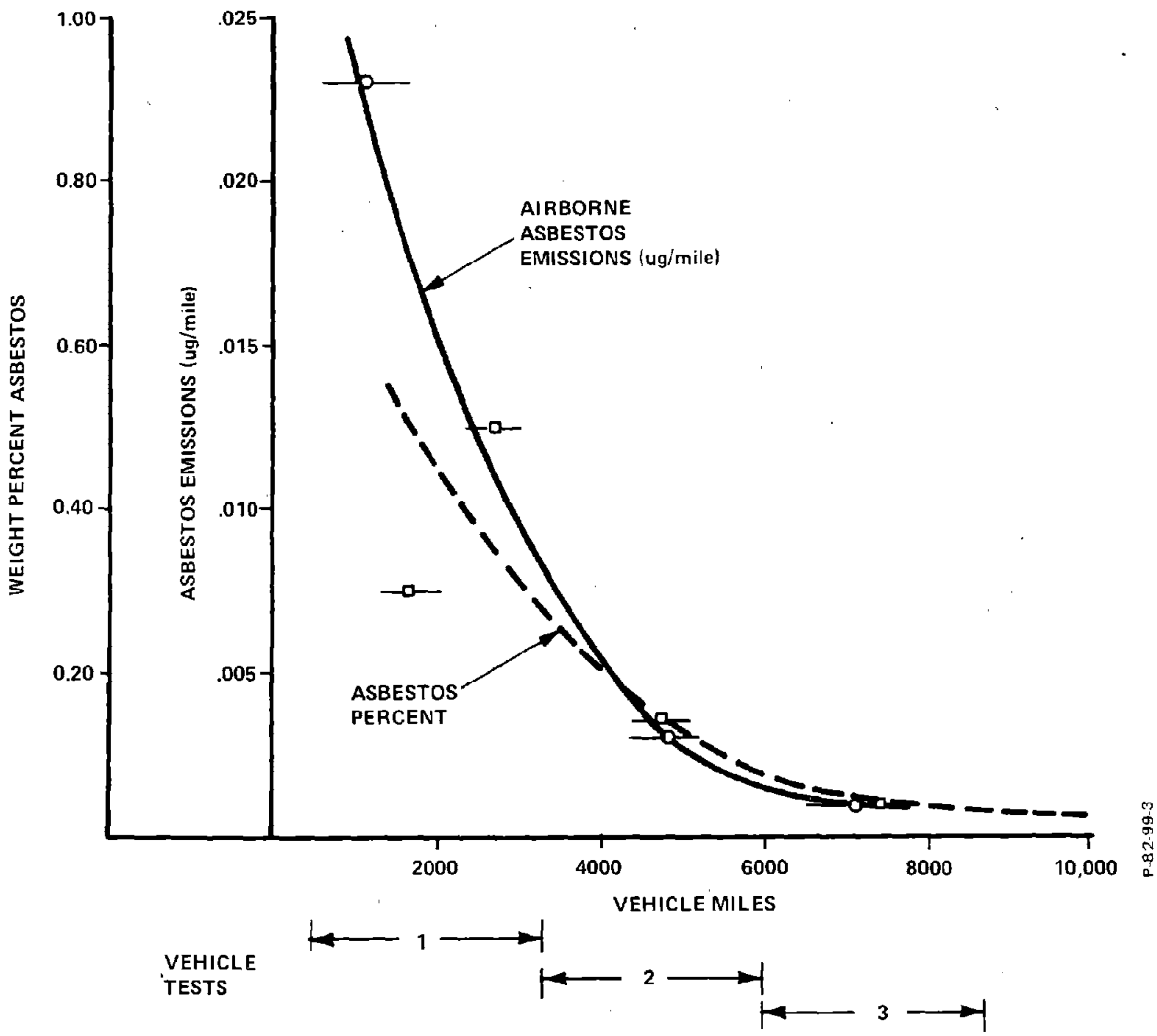


Figure 9-3 - Decrease in Clutch Airborne Asbestos Emissions with Continued Normal-Duty Service

- The ratio of drum brake/disc brake emissions decreases with use: for the Burnish schedule, the ratio was 1.55; for the A.B. Baseline schedule, the ratio was 1.53; and for the Detroit Traffic schedule, the ratio decreased to 1.10.

9.5.3 Heavy (Abusive) versus Moderate Duty

The asbestos emission results for the 10-Stop Fade and 15-Stop Fade - considered heavy-duty or abusive tests - and the corresponding A.F. Baseline and Final Baseline are given in Table 9-28.

Table 9-28 - Asbestos Emission from Heavy-Duty Tests

Location	Vehicle Test	10-Stop Fade (ug/mile)	A.F. Baseline (ug/mile)	15-Stop Fade (ug/mile	Final Baseline (ug/mile)	10-Stop Fade / Detroit Traffic
Right Front Disc Brake	1	100.60	29.61	2040.76	28.53	42.8
	2	79.13	6.69	56.52	2.91	6.2
	3	8.82	3.51	34.91	7.88	18.3
	Totals	188.55	39.81	2132.29	39.32	Average: 22.4
Right Rear Drum Brake	1	22.58	5.21	5.66	5.67	2.0
	2	146.64	3.28	2.77	2.83	26.7
	3	5.03	0.32	1.80	19.50	8.0
	Totals	174.25	8.81	10.23	28.00	Average: 12.2

The following trends are noteworthy:

- The right front brake emissions were higher than the corresponding rear brake results as only the front brake experienced the true fade temperatures because of the brake designed balance.
- The 15-Stop Fade total emissions for the front brake were higher than for the 10-Stop Fade total, again because of the higher temperatures experienced, as compared to the 10-Stop Fade.
- The A.F. Baseline and Final Baseline total emissions were higher than the corresponding A.B. Baseline total given in Table 9-25 by a factor of approximately 4.4 for the front brake.
- The right rear drum brake show higher emissions for the 10-Stop Fade than for the 15-Stop Fade due to a shift in duty to the rear brakes as the front brakes fade during their first heavy-duty experience.

The above total-wheel asbestos emission trends indicate that there is a rise in total asbestos emissions produced with high temperature use. This trend was only partially reflected in a slight asbestos percent increase indicated earlier in Tables 9-16, 9-17, and 9-18. The greatest portion of the asbestos emissions increase was due mainly to the larger-than-normal amount of wear debris produced during and after the heavy duty and high temperatures experienced by the friction materials, as indicated in Tables 9-9, 9-10, and 9-11, and considering the mileages for each schedule.

The following observation was also noteworth in the comparison of moderate and heavy-duty tests:

- The ratio of asbestos emissions for the 10-Stop Fade to Detroit Traffic Tests (far right column of Table 9-27) was higher than the ratio of asbestos emissions for the Burnish to A.B. Baseline plus Detroit Traffic test average (far right column of Table 9-26). The order of decreasing asbestos emissions from brakes can be summarized:

  Fade (or heavy-duty stops)

  Burnish

  A.B. Baseline + Detroit Traffic
  (moderate driving)

  ↓ Decreased Asbestos Emissions

9.5.4 Effects of Friction Materials

The data for the asbestos emissions were rearranged for each brake as shown on Table 9-29. This is the best way to compare the results due to the different friction materials. The following trends were noted:

Table 9-29 - Comparison of Asbestos Emission Generated by Different Friction Materials

Duty	Schedule	Asbestos Emissions (µg/mile)					
		Vehicle Test 1		Vehicle Test 2		Vehicle Test 3	
		Front	Rear	Front	Rear	Front	Rear
Moderate	Burnish	16.70	59.09	36.35	23.43	7.21	11.67
	A. B. Burnish	2.23	9.22	4.71	2.38	1.96	1.98
	Detroit Traffic	2.35	11.07	12.75	5.50	0.48	0.63
	Totals	21.28	79.38	53.81	31.31	8.65	13.98
Heavy to Abusive	10-Stop Fade	100.60	22.58	79.13	146.64	8.82	5.03
	A. F. B seline	29.61	5.21	6.69	3.28	3.51	0.32
	15-Stop Fade	2040.76	5.66	56.52	2.77	34.91	1.80
	Final Baseline	28.53	5.67	2.91	2.83	7.88	19.50
	Totals	2199.50	39.12	145.25	155.52	55.12	26.75

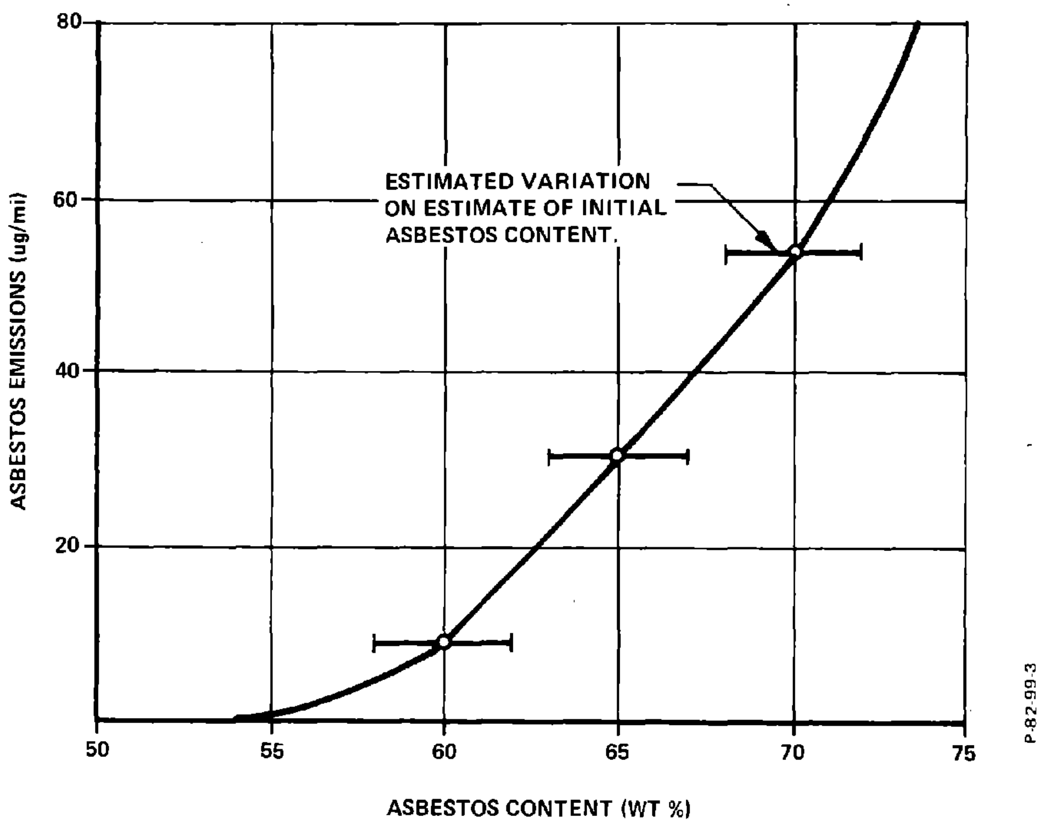


Figure 9-4 - Variation of Asbestos Emissions During Moderate Duty With Asbestos Content of Disc Pads

- For the disc pads, there was an increase in asbestos emissions for increases in pad asbestos content:

Vehicle Test	Estimated Asbestos Content (Weight percent)	Asbestos Emissions (μg/mile)
3	60	8.65
1	65	21.28
2	70	53.81

These data are plotted in Figure 9-4 and show an almost linear relationship, predicting a zero asbestos emission content when the pad asbestos content falls below 55 weight percent.

- There was no such trend for the drum brake data.
- Both the disc pads and the drum linings of vehicle test 3 showed the lowest asbestos emissions of all three tests. Both the disc pads and the secondary linings contained brass chips which may have been responsible for the almost complete conversion of the asbestos in the brake emissions of the respective wheels.

9.5.5 Airborne versus Sump versus Surfaces Samples

The comparisons of the asbestos emissions found in the sump, surfaces and airborne sample locations can be determined from the data given in Table 9-30. The data can be summarized and compared (Table 9-31):

Front Disc Brake Trends

- For the moderate-duty tests, the airborne asbestos emissions were 6.12 percent of the total emissions. The surface samples contributed 76.80 percent while the sump samples were 17.02 percent.
- For the heavy-duty tests, and as a result of the severely burnished rubbing surfaces, the airborne asbestos emissions were only 0.71 percent and the sump samples 6.71 percent as the surfaces samples increased to 92.58 percent.

Rear Drum Brake Trends

- For the moderate tests, the airborne asbestos emissions were 2.00 percent of the total emissions. The surfaces samples contributed 88.28 percent while the sump samples were 9.72 percent.

Table 9-30 - Comparison of Asbestos Emissions for Various Sample Locations (μg/mile)

Duty	Vehicle Test	Schedule	Front Disc Brake			Rear Drum Brake		
			Sump	Surfaces	Airborne	Sump	Surfaces	Airborne
Moderate	1	Burnish	6.77	9.42	0.51	N/A	58.11	0.92
		A. B. Baseline	0.04	1.04	1.15	1.01	7.47	0.74
		Detroit Traffic	0.35	1.91	0.09	0.39	10.50	0.18
	2	Burnish	3.45	32.70	0.20	4.63	18.52	0.28
		A. B. Baseline	0.33	4.29	0.09	0.62	1.68	0.08
		Detroit Traffic	0.09	10.92	1.74	2.17	3.29	0.04
	3	Burnish	2.64	4.12	0.45	2.01	9.46	0.20
		A. B. Baseline	0.77	0.72	0.47	0.04	1.88	0.06
		Detroit	0.03	0.36	0.48	0.13	0.49	0.01
		Averages:	1.61	7.28	0.58	1.38	12.38	0.28
Heavy or Abusive	1	10-Stop Fade	57.13	41.77	1.70	--	22.11	0.47
		A. F. Baseline	3.52	25.12	0.97	0.71	4.43	0.07
		15-Stop Fade	78.69	1957.40	4.47	--	5.47	0.19
		Final Baseline	1.90	24.85	1.78	1.61	4.05	0.01
	2	10-Stop Fade	7.83	70.85	0.45	--	154.50	0.36
		A. F. Baseline	0.47	5.70	0.52	--	5.24	0.02
		15-Stop Fade	1.48	53.85	1.19	--	3.11	0.05
		Final Baseline	0.16	2.61	0.14	1.30	1.30	0.23
	3	10-Stop Fade	3.40	3.64	1.78	2.66	2.34	0.03
		A. F. Baseline	0.15	2.94	0.44	0.12	0.19	0.01
		15-Stop Fade	7.22	24.49	3.20	0.97	0.78	0.05
		Final Baseline	0.27	7.25	0.36	3.67	15.81	0.02
		Averages:	13.52	185.04	1.42	1.58	18.28	0.13

Table 9-31 - Summary Comparison of Surfaces, Sump, and Airborne Samples

BRAKE SYSTEM	SUMP (ug/mile)	SURFACES (ug/mile)	AIRBORNE (ug/mile)
Disc Brake			
Moderate Duty	1.61	7.28	0.58
	(17.02)*	(76.86)	(6.12)
Heavy Duty	13.52	185.04	1.42
	(6.71)	(92.58)	(0.71)
Drum Brake			
Moderate Duty	1.38	12.38	0.28
	(9.72)	(88.28)	(2.00)
Heavy Duty	1.58	18.28	0.13
	(7.90)	(91.45)	(0.65)
Average (wt)	4.52	55.75	0.60
	(7.33)	(91.68)	(0.99)

*Data in parentheses are the percents of the total samples for the condition considered.

- For the heavy-duty tests, and as a result of redistribution of the sump sample, the airborne asbestos emissions were only 0.65 percent and the sump samples 7.90 percent as the surfaces samples increased to 91.45 percent.

9.6 CHANGES IN LINING WEAR RATE AFTER USE AT HIGHER TEMPERATURES

One of the goals of the project was to ascertain the changes in lining wear rate and the corresponding asbestos contents after preconditioning at elevated temperatures. The lining wear changes are given in Table 9-32.

The A.B. Baseline schedule (and the other Baselines) consisted of a three-day Detroit Traffic driving test. The Detroit Traffice schedule consisted of twelve days of the same road pattern. Thus one-fourth of the Detroit Traffic schedule was equivalent to the A.B. Baseline schedule. The data for the front brakes showed good consistency for each of these schedules. The data for the rear brakes showed wider variations.

The A.F. Baseline and Final Baseline schedules were run after the 10- and 15-Stop Fade schedules followed by a Reburnish schedule. The right front brake indicated >550°F during the fades and had a wear factor approximately 250 percent greater than the one-fourth Detroit Traffic schedule. The left front brake indicated only 300-370°F during the 10-stop fade (due to increased intervals) and had a wear factor approximately 120 percent greater than the A.B. Baseline and the one-fourth Detroit Traffic schedules.

9.7 RESULTS OF GASEOUS EMISSIONS ANALYSES

9.7.1 Summary of Analytical Methods Attempted

Analysis of the gaseous emissions was made difficult by the large quantities of water and carbon dioxide present in the samples. Calculations were made which indicated that the flow through the rotating seals was approximately 0.5 to 0.7 percent of the total. Even when gaseous emissions collections were made during their peak formation such as the fade tests, sufficient quantities of untreated air entered through the rotating seals (downstream of the Drierite and calcium oxide) to present serious analytical interferences.

Several different analytical schemes were used and proved only partially successful. Initially, the entire contents of the charcoal gas traps were condensed in the gas handling system described in Section 8.5.2. Traps cooled with acetone-dry ice and LN_2 were employed. The noncondensable gases proved to be essentially 100 percent air; no other gases could be detected except for a small amount of CO_2. When all this gas was pumped away and the LN_2 removed, the trap was found to contain 100 percent CO_2. In one instance, the CO_2 vapor pressure built up so fast that a stop-cock barrel was shot out of the system. In attempts to trap heavier gases and reduce the danger of a high pressure

Table 9-32 - Change in Lining Wear Rate After Operation at Increased Temperatures

					FRONT BRAKES				REAR BRAKES			
					RIGHT (SHROUDED)		LEFT (NORMAL)		RIGHT (SHROUDED)		LEFT (NORMAL)	
SCHEDULE	Vehicle Test No.	Miles	Stops	Pedal Appl.	Max. Temp (°F)*	Wear Per Stop (Mg)	Max. Temp. (°F)	Wear Per Stop (Mg)	Max. Temp. (°F)	Wear Per Stop (Mg)	Max. Temp. (°F)	Wear Per Stop (Mg)
A.B. BASELINE	1	328	682	1382	310	2.73	170	1.89	220	1.20	170	1.78
	2	348	483	1330	320	2.38	240	2.30	200	2.50	240	2.42
	3	368	520	1370	330	5.40	170	2.68	240	3.64	180	1.54
	Avg.					3.50		2.29		2.45		1.91
DETROIT TRAFFIC (÷4)	1	358	562	1412	360	2.53	170	1.87	260	2.63	180	2.26
	2	357	570	1375	330	1.80	210	1.55	180	2.33	240	1.83
	3	343	750	1507	300	1.67	150	1.67	240	0.61	150	1.55
	Avg.					2.00		1.70		1.86		1.88
A.F. BASELINE	1	356	480	1432	~550	6.95	360	2.37	375	2.12	340	4.95
	2	339	542	1045	550	5.12	370	2.36	290	0.52	320	1.76
	3	347	843	1298	520	2.50	300	1.39	370	0.73	320	1.59
	Avg.					4.86		2.04		1.12		2.77
FINAL BASELINE	1	353	594	1444	~625	6.28	275	2.06	325	0.83	285	1.90
	2	326**	464**	1202**	600	4.07	310	1.47	280	-***	260	1.79
	3	352	352	1433	560	4.87	330	2.91	430	1.42	330	1.73
	Avg.					5.07		2.15		1.13		1.81

*Before Test

**Data for only 11 circuits.

***Brake fluid in friction materials - no result.

build-up, the CO_2 was allowed to evaporate into the vacuum after the LN_2 trap was replaced with acetone-dry ice. The final fraction proved to be mainly CO_2 and water with traces of hydrocarbons.

An attempt to eliminate CO_2 and H_2O was made by passing the gases from the charcoal traps through Drierite and calcium oxide traps placed between the gas handling and the gas collection systems. This proved partially successful.

The traces of gases obtained gave only small peaks in gas chromatography with the thermal conductivity detector (T.C.D.). This problem was overcome by employing the flame ionization detector (F.I.D.) for the hydrocarbon analyses. However, all attempts proved fruitless in detecting anything other than minor amounts of C_1's to C_3's. Because of all of these difficulties, it was decided to minimize the effort devoted to future gas analyses.

In a last attempt to detect gaseous emissions products the gas collection system was connected directly to the gas injector of the gas chromatograph and the sample was analyzed simultaneously with both T.C.D. and F.I.D. This method proved successful for the fade test products. Although the T.C.D. detected only the major inorganices, the F.I.D. gave several peaks discussed in the following section. This method indicated that the initial tests with T.C.D. alone did not have adequate sensitivity for the organic products in the C_4-C_7 range where the entire test was sampled. The major drawback of this revised method of direct injection is that it is impossible to analyze the total volume of products obtained.

9.7.2 Gaseous Emissions Detected

Table 9-33 lists the data from the analysis of the gaseous emissions from vehicle test 1 while Table 9-34 lists the data from vehicle tests 2 and 3.

For vehicle test 1, the activated-charcoal gas traps from the Burnish and Detroit Traffic tests showed traces of C_1 to C_4 hydrocarbons in large quantities of air, carbon dioxide, and water (Table 9-33). No other materials could be found.

For the 10-Stop Fade test, the initial gases released from the traps again showed traces of C_1 to C_4 hydrocarbons when analyzed. The traps were then connected directly to the gas chromatrograph (G.C.) as described in the previous section. The charcoal gas trap samples from the right front brake, 10-Stop and 15-Stop Fade schedule of all vehicle tests were analyzed with a Porapak column. At times, the large amount of air and CO_2 gave slightly earlier than normal elution times as compared to the calibration blend. The same sample was also run on a W-98 silicone gum rubber column. Table 9-35 lists the elution order of different compounds from the Porapak column. The table lists the compounds used for calibration, those detected, and possible compounds whose elution occurs between the calibration compounds. Table 9-36 lists the elution

Table 9-33 - Data From Analysis of Gaseous Emissions (Vehicle Test 1)

	Front Disc Brake		Rear Drum Brake		Clutch
Schedule	Charcoal Traps	Condensable Gas Trap	Charcoal Traps	Condensable Gas Traps	Charcoal Traps
Burnish	Much CO_2, air, H_2O, trace CH_4	Water	Much CO_2, air, H_2O, trace CH_4	Water	Much CO_2, air, H_2O trace CH_4, C_2H_6, C_3H_8, C_4H_{10}'s
Detroit Traffic	Much CO_2, air, H_2O trace CH_4	Water	Trace CH_4, C_3H_8, i-C_4H_{10}	Water	Much CO_2, air, H_2O trace CH_4, C_2H_6
10-Stop Fade	C_4 to C_8's: benzene, toluene, phenol, and cresols		CO_2, Air, H_2O CH_4, C_3H_8, i-C_4H_{10}, and high M.W.'s*	Water	Much CO_2 air, H_2O
A. F. Baseline	Not sampled	Not sampled	Not sampled	Not sampled	Not sampled
15-Stop Fade	Low M.W. C_4-C_6	1 Peak MW $\sim C_{14}$	CO_2, Air, H_2O	Water	Much CO_2 air, H_2O trace CH_4
Final Baseline	Not sampled	Not sampled	Not sampled	Not sampled	Not sampled

*M.W. = Molecular Weight

Table 9-34 - Data From Analysis of Gaseous Emissions (Vehicle Tests 2 and 3)

		Front Disc Brake		Rear Drum Brake	
	Schedule	Charcoal Traps	Condensable Gas Trap	Charcoal Traps	Condensable Gas Traps
Vehicle Test 2	A.B. Baseline	CO_2, air H_2O, trace CH_4	Not analyzed	CO_2, air H_2O, trace CH_4	Not analyzed
	Detroit Traffic	Benzene, tolueme, up to cardanol		CO_2, air H_2O, trace C_1 to C_8	
	10-Stop Fade	Some high M.W.* peaks		Some high M.W. peaks	
	15-Stop Fade	Some high M.W. peaks			
Vehicle Test 3	Burnish	CO_2, Air, H_2O, trace CH_4		CO_2, air, H_2O trace CH_4	
	Detroit Traffic	CO_2, Air, H_2O, trace CH_4 plus high M.W. peaks		CO_2, H_2O, air C_2H_6 + C_2H_6 + traces C_4 to C_8	
	10-Stop Fade	Some high M.W. peaks		Not analyzed	
	15-Stop Fade	Some high M.W. peaks			

*M.W. = Molecular Weight

Table 9-35 - Elution Order From Porapak Q

	Calibrant	Detected	Possible
Air	X	X	
Carbon monoxide	X	X	
Methane	X	X	
Carbon dioxide	X	X	
Ethane	X	X	
Water	X	X	
Propane	X	X	
Methanol	X		
Formaldehyde			
Acetaldehyde			
Butane	X	X	
Ethanol	X		
Propylene oxide			
Propionaldehyde			X
Acetone	X		
Isopropanol			X
Acetic acide			
Methyl acetate			
Propanol			
Pentane	X	X	
Isobutraldehyde			X
Butraldehyde			X
2-Butanone			
Methyl-ethyl ketone			
Ethyl acetate			
Isobutanol			
Hexane	X	X	
Butanol			
Benzene	X	X	
C_7^+		X	

Table 9-36 - Elution Order From W-98

	Calibrant	Detected	Possible
Pentane			X
Benzene	X	X	
Toluene	X	X	
m+p-Xylene	X	X	
o-Xylene	X	X	
Benzaldehyde	X		X
Phenol	X	X	
1,2,3TM-Benzene	X		
Indene	X		X
o-Cresol	X	X	
m-Cresol	X	X	
2,6DM-Phenol	X		X
1,2,3,5TM-Benzene	X		
2,4DM-Phenol	X		
n-Dodecane	X		
n-Hexadecane	X		

order of different compounds from the W-98 column. The table lists the compounds used for calibration, those detected, and other possible compounds expected.

9.7.3 Shroud Extract Analysis

During normal fade tests, a dark brown cloud of high molecular weight organics with a pungent odor appeared after the seventh to fifteenth fade stops for each front brake. During the 10-Stop Fade of vehicle test 1, a cloud was observed for the left front brake only as the brake shroud prevented any such release for the right front brake. The inside surface of the shroud was covered with a "tarry" layer which presented the same pungent odor after all fade tests.

The G.C. chromatogram of the shroud extracts from the 10-Stop and 15-Stop Fade tests of all vehicle tests were chromatographed on an OV-101 column. The results indicated that the shroud extract contained organics with molecular weights higher than n-dodecame [molecular weight 170 and boiling point 214°C (420°F)]. Cardanol is present in all samples.

SECTION 10

ESTIMATED EMISSIONS FOR CARS AND TRUCKS

10.1 APPROACH

The purpose of this section is to develop an estimate of total brake and clutch emissions from the U.S. population of motor vehicles in use on the roads and highways. Inputs include all of the test results described earlier in this report, together with a supplementary data base on U.S. motor vehicle population and usage and on friction material usage and consumption obtained from other sources.

Because of the uncertainties in all of the data available, emissions can only be considered as a broad range, rather than as a single value, with the expectation that the true average emissions for both individual vehicles and the motor vehicle population in general will be within the range of values calculated below.

10.2 SUPPLEMENTARY DATA BASE

The data base reported in the accompanying tables was obtained from a wide variety of trade publications and from industry and government contacts. Credit is given to the sources of major contributions. Although they vary considerably in quality, the data are, in general, adequate for the purpose of estimating total annual emissions, because emissions themselves can vary so widely from vehicle to vehicle, from operator to operator, and from locality to locality.

10.2.1 Number of Vehicles in Use

Table 10-1 lists the total U.S. motor vehicle population as estimated by both Department of Transportation (DOT) (National Highway Traffic Safety and Federal Highway Administration)(10-1)* and by the R. L. Polk Company.(10-2) The Polk census is said to be more precise because it eliminates multiple registrations of the same vehicle. Polk considers that DOT estimates may be as much as 13 percent too high. Both Polk and DOT omit military vehicles, but include all other motor vehicles that are state-licensed including police cars, school buses and the like. Independently, the General Services Administration reports that 190,000 Department of Defense vehicles are in use world-wide.

Table 10-2 lists the U.S. braked trailer population and Table 10-3 lists the U.S. motor vehicles with dry clutches.

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*Numbers in parentheses refer to References at end of section.

Table 10-1 - U. S. Braked Motor Vehicle Population

Private Passenger Cars			
(R.L. Polk Estimate 7-1-71: 83,137,324)			
D.O.T. Estimate 7-1-72:			96,397,000
Trucks:			
(R.L. Polk Estimate 7-1-71: 18,462,287)			
D.O.T. Estimate 7-1-72: (Includes 897,456 Truck Tractors)			20,800,000
Light	Under 6000 lbs GVW*	12,109,000	
	6 -10,000	4,952,000	
Medium	10-14,000	125,000	
	14-16,000	125,000	
	16-19,500	645,000	
	19.5-26,000	1,290,000	
Heavy	26-33,000	395,000	
	Over 33,000	1,165,000	
Buses:			
D.O.T. Estimate 7-1-72			403,000
Miscellaneous Motor Vehicles: motor cycles, etc.			
D.O.T. Estimate 7-1-72			3,787,000
Total Motor Vehicles in Use**			
D.O.T. Estimate 7-1-72			121,400,000

*Cross vehicle weight; estimates from 1970-71 sales data extended by this study.

**This total includes approximately 1.5 million public vehicles (450,000 cars, 920,000 trucks, and 185,000 buses), but does not include 190,000 Department of Defense vehicles in worldwide use.

Table 10-2 - U. S. Braked Trailer Population

Class	Number In Use	Percent With Brakes	Number With Brakes
Recreational			
Travel	1,800,000	95	1,710,000
Camping	1,200,000	20	240,000
Boat	2,500,000	35	875,000
Miscellaneous (Animal, Utility, etc.)	1,700,000	80	1,360,000
Commercial			
Utility	1,000,000	60	600,000
Trucking			
Full	278,000	100	278,000
Semi	1,552,000	100	1,552,000
			6,615,000

Table 10-3 - U. S. Motor Vehicles With Dry Clutches

Vehicle Type	Number Of Vehicles In Use	Percent Containing Clutches With Asbestos	Number Of Dry Clutches
Passenger Cars			
Domestic	87,100,000	15	13,064,000
Imported	9,300,000	90	8,370,000
Trucks and Buses			
Light	17,100,000	75	12,900,000
Medium	2,600,000	95	2,470,000
Heavy	1,600,000	100	1,600,000
			38,404,000

Source: estimate made from industry canvas.

Table 10-4 - Yearly Additions to U. S. Braked Vehicle Population

New Vehicles Placed in Service (Calender Year 1972):		
Passenger Cars:		
Net U.S. Production	9,312,502	
Net Imports	1,593,605	
Total		10,906,107
Trucks:		
Total (estimated)		2,600,000
	Estimate Total:	13,506,107

Source: Wall Street Journal

The DOT estimate of 117-million total vehicles, including 20.8-million trucks, is probably sufficiently accurate for estimating brake emissions for 1972. It should be noted that the net growth in vehicles each year is given approximately by the sum of U.S. cars, trucks and other vehicles sold plus imports sold (all adjusted for exports) (Table 10-2) less annual retirement of about six- to seven-million cars and one-million trucks.(10-3, 10-4, 10-5) The scrappage rate tends to rise and fall with the sales rate and may well have been closer to eight-million cars than to seven-million for 1972. Figures are not yet available.

Assuming a total retirement of nine-million vehicles, the net growth in vehicles for 1972 was approximately 4.5 million:

10.9	million cars sold
+ 2.6	million trucks sold
13.5	million total
- 9.0	million scrappage
4.5	million net growth

The net growth in car and truck registrations from 1961 to 1971 averaged 3.12-million vehicles per year and will probably tend to follow the same patterns over the near future.

10.2.2 Motor Vehicle Usage

Table 10-5 shows the approximate total number of miles traveled by all U.S. motor vehicles to be 1.249-trillion miles for 1972, according to a recent DOT estimate(10-1). This total is said to be growing at a 4.5- to 5.2-percent annual rate. To accomplish this mileage, about 100 billion gallons of motor fuel were consumed for an overall average of a little over 12 miles per gallon. The detailed breakdown of mileage by vehicle type and roadway type (Table 10-6) was adjusted for 1972 total mileage from 1970 DOT data.

Roadway mileage and usage are further identified in Table 10-6 by type of surface and by locale, whether urban or rural. More insight into vehicle usage is given in Tables 10-7 and 10-8 where motor vehicle usage is classified by the purpose of the trip and length of the trip. All of these factors cast light, to some extent, on the degree of vehicle brake usage and emissions.

10.2.3 Estimates of Brake Usage and Abuse

Brake usage varies widely from gentle to abusive. In the following paragraphs the term abusive braking will be defined and its extent will be explored.

Table 10-5 - Motor Vehicle Usage by Vehicle Type and Roadway

Type of Vehicle	Billions of Vehicle Miles Traveled By Road Type and Location*				Average Annual Mileage Per Vehicle (1970)
	Local Rural	Main Rural	Urban	Total Mileage	
Passenger Cars	109*	337	534	980	9,978
Motorcycles and Motorbikes	- *	-	-	10.9	3,605
Buses:				6.	13,306
School	-	-	-	-	7,274
Commercial	-	-	-	-	32,591
Trucks-Total	35	119	91	245	11,450
Single Unit Trucks	33	88	77.	198	9,807
Truck Combinations	1.9	31	14	47	41,903
Total-all vehicles	150	464	635	1,249	10,076

*Blanks indicate insufficient data. Other data are adjusted for 1972 total analysis from 1970 D.O.T. breakdown on best-estimate basis.

**Weighted total average

Table 10-6 - Type and Usage of Public Roads

Road Type	Miles of Road	Billions of Annual Miles of Vehicle Travel (1972 estimate)
1. By Classification		
Interstate (42,500 authorized)		
Rural	30,000	117
Urban	5,000	113
Primary-Highways	705,000	
Rural	---	222
Urban	---	153
Secondary Highways	2,990,000	
Rural	---	275
Urban	---	92
Municipal Streets		277
2. By Location		
Rural	3,169,000	---
Urban	561,000	---
3. By Quality		
Surfaced	784,000	---
Non-surfaced	2,946,000	---
Grand Totals	3,730,000	1,249

Source: World Almanac, 1973 and
1972 Automobile Facts and Figures; adjusted

Table 10-7 - Motor Vehicle Usage by Purpose of Trip

Purpose of Trip	Proportion of Total Use	Average Trip Length
Earning a living (driving to work, etc.)	42.1%	10.2 miles
Family business	19.6	5.5
Educational	5.0	4.7
Social (includes vacations)	33.3	13.1

Table 10-8 - Motor Vehicle Usage by Length of Trip

Length of Trip (one way)	Percentage of Trips	Proportion of Total Use Miles, Percent
Under 5 miles	54.1	11.1
5 -10	19.6	13.8
10-15	13.8	18.7
15-20	4.3	9.1
20-30	4.0	11.8
30-40	1.6	6.6
40-50	0.8	4.3
50-100	1.0	7.6
Over 100	0.8	17.0
	100.0	100.0%

Average trip length = 8.9 miles

DOT Preliminary Survey 1969-70

Abusive braking, with the organic-bonded friction materials used almost universally on motor vehicles today, implies heating the bulk friction material to temperatures above about 500 to 600°F. At these temperatures, the phenolic resin binders gradually pyrolyze, weaken, and become brittle, allowing wear to increase rapidly. Because degradation is a time-temperature phenomenon, total brake-use history is important.

Overheating can be caused by one or a combination of the following:

Dragging brakes caused by system defect or operator error.

Repeated use of brakes to retard the vehicle on a long downgrade.

Repeated high-speed stops.

Maladjustment.

Severe vehicle overloading.

Partial brake system failure, overworking one or more brakes.

The degree of overheating is further influenced by ambient air temperature, wind velocity and relative direction, air flow around the brake (design) and use of engine braking to assist the foundation brakes.

In predominantly flat terrain and on most interstate-quality highways with gentle grades, the need to use brakes to overcome gravity is minimal. Here, brake overheating is rare and usually comes from abusive use as in the fade tests carried out under this program.

In very hilly or mountainous regions, overheating can occur quite easily as was demonstrated by a team of professional test drivers on cross country runs in 1967. Zechel, et.al.[10-6], described a study where a group of professional test drivers drove a total of 44,000 miles with six 1966 U.S. passenger cars in order to perform an "Automotive Brake Evaluation Under Customer Usage Conditions." Results of this trip (see Table 10-9) show that abusive temperatures were reached only in mountainous regions (and in the hot and hilly Los Angeles traffic for one disc brake car). Intentionally aggressive braking behavior in Detroit, St. Louis, New York, and other areas of heavy traffic failed to produce excessively high brake temperatures.

The proportion of mountain driving mileage on these trips was as follows: Eastern leg, 7.8% of the total; Western leg, 7.4%, of which 2.4% was in Los Angeles traffic. Repeated runs were intentionally made over some of these mountain roads for increased severity of the test. Because we have shown that total emissions tend to increase with abusive braking, its prevalence will be explored further.

Table 10-10 gives the results of an attempt to estimate the proportion of U.S. driving that takes place in predominantly hilly or mountaninous areas where long steep grades are common. Basic data on

Table 10-9 - Results of Cross-Country Brake Test Trip

	Maximum Brake Temperatures (°F)			
	Drum Brakes (4 cars)		Disc Brakes (2 Cars) (not used on Eastern Trip)	
Local	Average Peak Temperature	Maximum	Car "E"	Car "F"
Eastern Trip:				
Highway and rural	250	350	---	---
N.Y. City traffic	343	390		
Peters and Potts Mountain	471	580	---	---
Western Trip:				
Los Angeles traffic	421	465	320	630
Other city traffic		360	300	410
Highway and rural in hilly areas	300	410	300	375
Rocky Mountains	526	650	430	748

Source: SAE Report SP 338 (1967)

*Report covers 44,180 miles of coast-to-coast driving by professional drivers using 6 different makes of passenger cars. Test were deliberately aggressive to generate maximum temperatures to check brake fluid boil.
Car "F" ran hotter on the front wheels by more than 300°F compared to the rear wheels.

Table 10-10 - Where Vehicles Are Used

	Estimated Total Annual Usage	
	Predominantly Flat Terrain with Infrequent, Gentle Grades	Steep Hills to Mountainous with Frequent, Long, Steep Grades
Plains States - 30, with 79 million vehicles	777 billion miles	Minor Amount
Partly mountainous States- 20, with 38 million vehicles Estimated Usage: 70% flat terrain 30% steep grades	328	144 billion miles
Totals	1,105	144
Percent of all driving	88.5%	11.5%
Type of Braking Expected	Normal	Severe to abusive brake use may be needed.

Source: Estimate made for this study.

miles driven in each state are readily available from DOT. The percentage of driving that takes place in mountainous areas, where abusive brake use may be necessary, is estimated to be 11.5% of all driving. The estimate is subjective, to a large degree, and may be high, but no better data have been located.

Table 10-11 lists some additional U.S. driving characteristics recently gathered by the American Petroleum Institute. Table 10-12 lists typical numbers of brake applications per mile as measured under this and other brake programs. It is an illustrative rather than an exhaustive study of the subject.

Figure 10-1 illustrates the frequency of high-g stops, as determined at the Highway Safety Research Institute of the University of Michigan [10-7]. This shows that 50 percent of all stops are less than 0.15 g (4.8 fps^2), 99 percent are less than 0.36g (11.6 fps^2) and 99.9 percent are less than 0.5g (16 fps^2). Carpenter[10-8] confirms one point on the University of Michigan curve and lends credibility to the data.

10.2.4 Asbestos in Friction Materials

Almost all of the commercial friction materials used for braking passenger cars and trucks today are based on the unique strength and thermal stability of natural asbestos (chrysotile) fibers. This has been true for over fifty years. Table 10-13 shows that the asbestos content of friction materials averages about 60 percent.

Table 10-14 lists the weights of the brake lining materials used in this program. They are typical of the weights of friction material used on passenger cars today and will be considered average for the calculations which follow.

Compilations of data on brake rotors and friction materials usage appear in Tables 10-15, and 10-16, and 10-17 respectively. Based on the data in Table 10-16, the total amount of asbestos contained in all of the automotive brake friction materials sold each year is calculated to be about 103 million pounds which corresponds to ~118 million pounds used prior to grinding. The two most knowledgeable sources[10-9,10-10] report that 90 to 120 million pounds per year are used. A report from IIT Research Institute suggests that 67 million pounds are used annually in brake linings[10-11]. A Bureau of Mines Report [10-12] based on 1968 data credits only 50 million pounds of asbestos to automotive use, a number the authors find to be much too small. Ignoring the two latter values, the three estimates of asbestos contained in linings range from 90 to 120 million pounds. Using the calculated value of 118 million pounds and assuming a 15-percent grinding and drilling loss, the maximum amount of asbestos incorporated in brake friction materials is taken to be 103-million pounds per year.

A compilation of data on clutch friction materials usage is given in Table 10-17. Based on these data, the total amount of asbestos contained in all automotive clutch friction materials sold each year is calculated to be about 4.5-million pounds.

Table 10-11 - Some U. S. Driving Characteristics

City	Average Daily Mileage	Average Speed	Daily Driving Time
Chicago	35	22.9	88 minutes
Houston	36	25.2	85 minutes
Los Angeles	32	24.7	70 minutes
Minneapolis-St. Paul	-	26.3	-
New York	38	25.4	85 minutes
Detroit Traffic test (this study)	110	17	7.0 hours

Source: American Petroleum Institute (except for last item)

Table 10-12 - Brake Applications Per Mile

Source	Type of Traffic	No. of Pedal Applications Per Mile	Total No. of Miles	No. of Stops Per mile	Average Deceleration fps
This study	Detroit traffic	4.4	8,091	2.6	4 to 6
University of Michigan		1.43			
Highway Safety Research Dept.	Ann Arbor and Michigan traffic	1.43	6,255	-	-
Zechel et al, (SAE SP-338)	Cross Country				
	Eastern trip (4 cars)	1.9	8,400	-	-
	Western trip (4 cars)	0.98	24,400	-	-

Source: as noted

Table 10-13 - Asbestos Content of Automotive Friction Materials

Vehicle and Brake Type	Average Percent Asbestos Content by Weight*
Passenger Cars	
Drum Linings	68 ± 5
Disc Pads	60 ± 5
Truck Segments	55 ± 5
Clutch Facings	50 ± 5
"Average composition" for use in the calculations in this report.	60

*Sources Estimates made for this study.

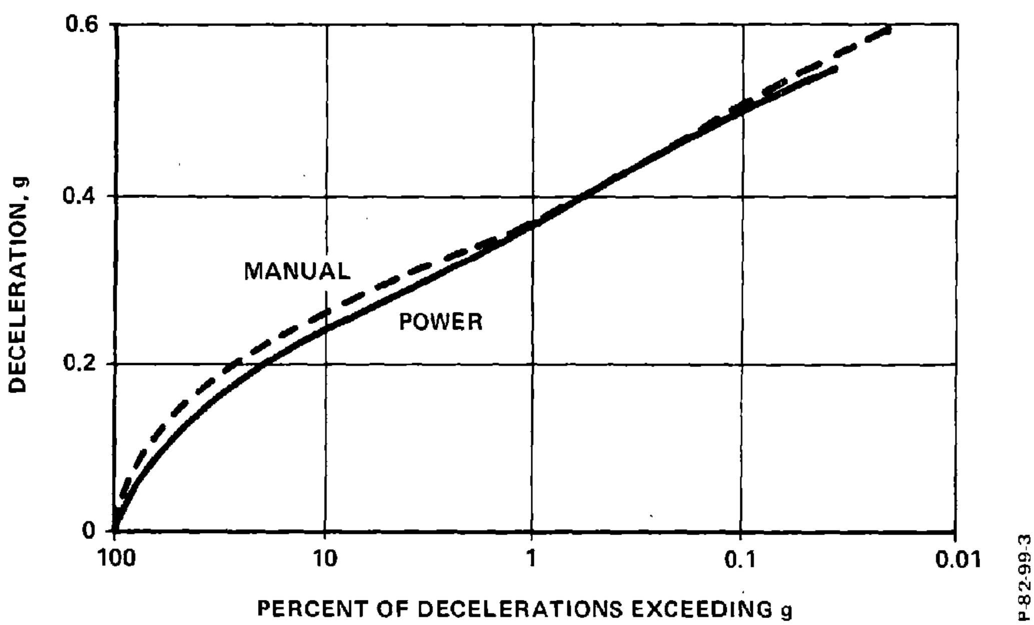

Figure 10-1 - Frequency Distribution of Braking Decelerations

Table 10-14 - Brake Friction Material Weights for Test Vehicle

Vehicle Test	Friction Material Description	Weight of Friction Material (gms)			
		Front Disc Pads		Rear Drum Linings	
		Right	Left	Right	Left
1	Inner Pad	95.8	93.8	-	-
	Outer Pad	117.4	116.5	-	-
	Primary Lining	-	-	108.1	106.4
	Secondary Lining	-	-	189.6	189.3
2	Inner Pad	106.4	106.1	-	-
	Outer Pad	105.0	105.6	-	-
	Primary Lining	-	-	104.9	102.4
	Secondary Lining	-	-	181.3	180.2
3	Inner Pad	115.3	113.0	-	-
	Outer Pad	152.3	160.3	-	-
	Primary Lining	-	-	113.2	113.7
	Secondary Lining	-	-	153.5	167.7
Average Per Wheel		231.3		311.3	
Average Per Axle		462.6		622.6	
Average Per Car		1085.2			

Table 10-15 - Number of Newly Surfaced Rotors Used Each Year

Rotors replaced	4,700,000
Rotors turned or ground	9,810,000
New rotors on new vehicles (1972)	54,060,000
Total rotors with new surfaces per year	68,570,000*
Percent of vehicles with new surfaces:	

$$\frac{68,570,000}{4 \times 123,323,000} \times 100 = 14\%$$

*Source; Stanford Research Institute Data.

Table 10-16 - Compilation of Annual Motor Vehicle Brake Friction Material Usage

Vehicle	Description	Amount Used Number and Unit	Weight Per Unit (lbs)	Total Weight (lbs)
Passenger Car	Front Disc Pads Only	9,660,000 Axle Sets	1.0	9,660,000
	Front Drum Linings Only	24,300,000 Axle Sets	1.8	43,700,000
	Rear Drum Linings Only	32,400,000 Axle Sets	1.3	42,100,000
Light Truck	Drum Linings	4,730,000 Vehicle Sets	5.0	23,700,000
Medium Truck or Bus	Drum Linings	670,000 Vehicle Sets	15.0	10,100,000
Heavy Truck	Drum Linings	781,000 Vehicle Sets	41.0	32,100,000
Miscellaneous (Trailers, etc.)	Drum Linings	----	----	10,000,000
				171,360,000

Source: Calculated from Friction Materials Standards Institute, D.O.T., and Stanford Research Institute Data.

Table 10-17 - Compilation of Annual Clutch Friction Material Usage

Vehicle	New	Annual Clutch Facing Use			Weight Per Unit (lbs)	Total Clutch Weight (lbs)
		Replacement		Total Units Installed		
		New	Rebuilt			
Passenger Cars:						
Domestic	900,000			1,710,000	0.88	1,500,000
Imports	1,350,000			2,580,000	0.60	1,550,000
Totals	2,250,000	1,760,000	280,000	4,290,000		
Trucks:						
Light	1,500,000*			3,100,000*	1.26	4,000,000
Medium	290,000*			600,000*	1.56	950,000
Heavy	190,000*			385,000*	2.26	680,000
Totals	1,980,000	935,000	1,170,000	4,085,000		
						8,740,000

*Estimated for ratio each truck size with clutch (Table 10-3)

Source: Estimated from market studies and industry sources for this study

Table 10-18 - Relative Brake Relining Frequency

Locale	No. of Wheels Relined Per 100 Vehicles Each Year
Northeast	74
South	49
Large cities (over 1 million)	82
Medium cities (100,000-500,000)	93
Small cities (under 25,000)	54
Rural areas	44
Average - U.S.	60*

*Approximately equivalent to relining all four wheels on 15% of all vehicles each year.

Frequency of brake relining is another measure of lining use, Table 10-18(10-13). Multiplying the relining rate of 15 percent per year times the vehicle population of 123 million and adding the number of new vehicles registered last year, 13.5 million, gives 32,100,000 vehicle sets as an estimate of annual friction materials usage. This is a somewhat smaller number than that derived in Table 10-16, probably because insufficient emphasis was given to medium and heavy trucks in these data. One word of caution is in order at this point: the amount of friction material worn away each year is significantly less than that which is installed for a variety of reasons to be discussed in the next sub-section.

10.2.5 Amount of Friction Material Actually Worn

For several reasons, the amount of brake lining (and asbestos) worn away during a year is significantly less than the total amount installed on vehicles. Brake linings are seldom completely worn away (due to the geometry of brake systems, perhaps 10 percent of the lining is still left on a brake when lining wear-through occurs). Linings are usually replaced in sets rather than piecemeal. As a consequence of this and other actions, about 25 percent of all brake linings is discarded at relining time. Furthermore, millions of vehicles are retired from service each year, many with brake linings that are far from worn out. Perhaps the average retired vehicle has about 1/3 of its usable lining remaining, or 1/3 x 90 percent + 10 percent = 40 percent of the installed weight of the lining.

Combining these figures, the amount of brake friction material worn away each year is calculated as follows:

	Total Brake Friction Material
Installed weight each year	171.4 million lbs
Less Discarded on relining - 25%	42.7 million lbs
Less discarded on vehicles retired	11.7 million lbs
(7 million cars x 2.38 lb x 40% = 6.7 + (0.75 million light trucks x 5 lbs x 40% = 1.5)+ (0.10 million medium trucks x 15 lbs x 40% = 0.6)+ (0.15 million heavy trucks x 41 lbs x 40% = 2.4)+ (miscellaneous = 0.5)	
Amount worn away, annually	117.0 million lbs

Employing the same reasoning for clutches, the amount of clutch material worn away is calculated as follows:

	Total Clutch Friction Material
Installed weight each year	8.76 million lbs
Less discarded on relining - 15%	1.31 million lbs
Less discarded on vehicles retired	0.89 million lbs
(1.5 million cars x 0.75 lbs x 40% = 0.45)+ (0.50 million light trucks x 1.26 lbs x 40% = 0.45)+ (0.10 million medium trucks x 1.56 lbs x 40% = 0.06)+ (0.15 million heavy trucks x 2.26 lbs x 40% = 0.13)	
Amount worn away, annually	6.56 million lbs

Summarizing, the combined total of brake and clutch friction material worn away annually is 117.0 + 6.6 = 123.6 million pounds. Assuming that the average asbestos content is 60 weight percent, the amount of asbestos worn away as friction material wear debris is $\sim$74 million pounds.

10.3 INTERPRETATION OF TEST RESULTS

10.3.1 Factors Influencing Rate of Emissions

Emissions measured during this program were generated by an intentionally severe schedule, one that is used by the industry to accelerate brake testing. Consequently, emissions were undoubtedly generated at a rate somewhat above average for the population as a whole.

Emissions per mile for a given brake can vary, for example, with the following:

- Composition of the friction material
- Composition, metallurgical structure and hardness of the cast iron rotor (drum or disc).
- Surface roughness of the rotor.
- Previous use (history) of the friction material - primarily thermal history, both recent and overall.
- Third-body contamination of the sliding interface by road dust, wear debris, rain water, salt and the like.
- Vehicle usage - miles driven: urban, surburban, rural, expressway.
- Vehicle weight, including passengers and cargo.
- Vehicle speed at beginning (and end) of stop.

- Deceleration (average or typical, as well as instantaneous).
- Frequency of braking due to traffic, terrain, and driver habits.
- Interface temperature, sliding speed, and unit load on the friction material.
- Roadway surface and grade.
- Air temperature, wind velocity, and wind direction relative to direction of vehicle motion.
- Brake design, including brake balance front to rear, and swept area in relation to vehicle weight and horsepower.
- Vehicle design including brake cooling adequacy.
- Operator habits and behavior - riding the brake, gentle stops versus rapid deceleration versus abusive deceleration, etc.
- Brake adjustment and maintenance - balance from side to side and front to rear.

Some of the above factors are not independently variable, but are mentioned for emphasis. Tires (radial versus bias belt), engine-transmission braking, suspension, and aerodynamic shape also influence vehicle braking to some extent.

During this test program, emissions were measured under the following sets of conditions:

- Seven different friction material formulations made by five different manufacturers.
- Disc versus drum brakes.
- New friction materials versus used friction materials.
- Freshly machined rotors versus polished (used) rotors.
- Moderate use versus abusive use under seven driving categories.

Emissions were examined for asbestos content using the best available techniques and confirmatory tests were conducted at two additional laboratories (Battelle and Johns-Manville). The program results for asbestos emissions were slightly higher and were chosen exclusively to calculate a maximum asbestos emissions estimate.

10.3.2 Weighting Factors

10.3.2.1 Distribution Weighting Factors

10.3.2.1.1 Location of Wear Debris

Disc brakes are designed to allow air to pass through them freely. Because of this open design they retain less wear debris than drum brakes. Consequently, the surfaces samples for the disc brake are essentially emitted samples. As indicated earlier, the disc brake emission collector collected all disc brake wear debris. It was fractionated into the following samples:

- airborne: these are the light particles which remain in the air-stream as it progress through the collector - in this program this material was collected on filters - and the particulates were presumed to be representative of disc brake wear debris which may remain airborne in the atmosphere for a period of time.
- surfaces: these are the heavier agglomerates which quickly fall to the ground or nearby surfaces - in this program this material was deposited on the bottom and inner surfaces of the shroud and on the brake parts.
- sump: these are the particles of brake debris remaining in the brake on the lining surfaces, in the rivet holes, and in the caliper.

The drum brake emissions collector also collected all of the drum brake wear debris. It fractionated into the following samples:

- airborne: there are light particles which remain in the air-stream as it passes through the collector - in this program this material was collected on filters - and the particulates were presumed to be representative of disc brake wear debris which may remain air-borne in the atmosphere for a period of time.
- surfaces: these are the heavier agglomerates which quickly fall to the ground or nearby surfaces - in this program this material was deposited on the inner surfaces of the shroud and on the brake parts.
- sump: these are the particles which remain on the brake drum and lining surfaces and in the rivet holes.

10.3.2.1.2 Comparison of Normal versus Shrouded Brakes

The effect which the shrouding produced on the quantity and distribution of the emissions for the right front disc brake and the right rear drum brake can be estimated as follows.

The data given earlier in Tables 9-9 and 9-10 for vehicle tests 1 and 2 show that the individual sump samples of wear debris collected after each schedule for the normal disc brake are comparable in amount to those of the shrouded disc brake. The totals are also comparable. On the other hand, the data given in Table 9-11 show that the cumulative sump sample, taken at the end of vehicle test 3, is significantly less than the total obtained from the summation of each individual schedule. Further, the total sump sample for vehicle test 3 is comparable in value to the average value collected for each schedule alone of vehicle tests 2 and 3. Consequently, the sump sample appears to achieve and maintain an average value independent of the mileage. When the debris is removed, the equilibrium value appears to reestablish itself.

The surfaces samples for the open brake behaves in a similar manner. The surfaces samples of the open brake were smaller (only 2.7 to 4.5 percent of the shrouded brake samples). The total surfaces sample for the left front brake, taken after vehicle test 3, was comparable to the maximum single value (for the Detroit traffic test - the longest mileage test), when individual values are taken after each schedule. Here again, an equilibrium value appears to establish itself.

The best estimate for the distribution of the disc brake wear debris when the brake is new can be made by considering the Burnish data of Table 9-13. After 174 miles, the distribution of emissions can be estimated.

9% returned in sump	
2% on surfaces	- calculated from open brake
4% airborne	- measured at shrouded brake
85% road dropout	- balance

The best estimate for the distribution of the disc brake wear debris for a use brake can be made from the data from vehicle test 3. After 2632 miles, the distribution from the open disc brake is as follows:

1.5% retained in sump	
1.4% retained on surfaces	- evaluated from open brake
7% airborne	- average from shrouded brake
91% road-dropout	- balance

As the brake is used, the amount retained in the brake remains constant, but the percent values for retention decrease to less than one percent.

The average for the airborne samples for 8100 miles is six percent. Thus the distribution for the well-used disc brake can be estimated as follows:

1% retained in brake

6% airborne

93% road drop-out

No major change in these relative proportions is expected for continued operation beyond the 8100 miles of the test to wear-out.

The data given in Table 9-9 for vehicle test 1 show that the amounts of sump sample debris collected after each schedule for the normal (unshrouded) drum brake are somewhat comparable to those of the shrouded drum brake. The totals are also somewhat comparable, although the total for the shrouded brake seems slightly low. The surfaces samples are slightly less for the normal drum brake and the overall totals for the entire test show that approximately 53 percent of the surfaces samples remained in the brake. The negative numbers for the sump samples are real. Since 80 percent of the sump sample from the previous schedule was reintroduced onto the brake drum prior to each following schedule, it was possible for the sample to redistribute in such a way that the sump sample decreased to a value less than the original amount added. The surfaces sample showed a corresponding increase so that the total debris generated was never a negative value for the shrouded brake. The normal drum brake could and did occasionally show a negative value for total debris.

The rear brake data given in Table 9-10 for vehicle test 2 was for the continued testing of the used original equipment rear brake linings from vehicle test 1. Thus each rear wheel started with the 80 percent sump debris addition (from vehicle test 1). The total debris collected from the shrouded brake for vehicle tests 1 and 2 were comparable. The total debris from the open brake was less for vehicle test 2 than for vehicle test 1. The only explanation feasible is as follows. The amount in the sump debris of this test is at an equilibrium level and there is no more physical room for the material. Thus it falls out of the wheel immediately and less debris is distributed to the surfaces in vehicle test 2 as compared to vehicle test 1.

The best estimate for the normal distribution of drum brake wear debris when the brake is new can be made from the Burnish data of Table 9-13. After 174 miles, the distribution of emissions can be estimated as follows:

16% retained in sump
29% retained on surfaces - calculated from open brake

1% airborne - measured at shrouded brake

54 road drop-out - balance

The best estimate for the distribution of drum brake wear debris for a used brake can be made by extending the data in Table 9-11 for vehicle test 3. For 2632 miles, the open drum brake accumulated the following:

Sump debris: 0.97 gm (9% of weight loss)

Surface debris: 1.91 gm (17% of weight loss)

Supplementary data from employees' vehicles and vehicles submitted for brake relines in local shops indicated the following trends for friction materials with an average life of 40,000 miles:

After 5000 miles:

Sump debris: ∿2 gm (∿10% of friction material wear)

Surfaces debris: ∿4 gm (∿18% of friction material wear)

After 25,000 miles:

Sump debris: ∿3 gms (∿5% of friction material wear)

Surfaces debris: ∿10 gms (∿12% of friction material wear)

After 40,000 miles:

Sump debris: ∿4 gms (∿3% of friction material wear)

Surfaces debris: ∿12 gms (∿10% of friction material wear)

The trends are graphically illustrated in Figure 10-2.

Not all of the wear debris found in a brake is from the friction material itself. The analysis of a few samples for iron content indicated approximately 5-15 percent by weight is iron oxide which came from the rotor wear.

In this program, no driving or braking took place on dusty or salted roads. However, the average consumer would drive under these conditions at times and this would slightly alter the composition of the retained brake debris. For purposes of estimation, the average vehicle has linings that are 50 percent worn (at the 20,000 mile point on Figure 10-2) and the contributions to the atmosphere can be estimated in the following manner:

13% retained in sump

6% retained on surfaces

2% airborne

79% road drop-out

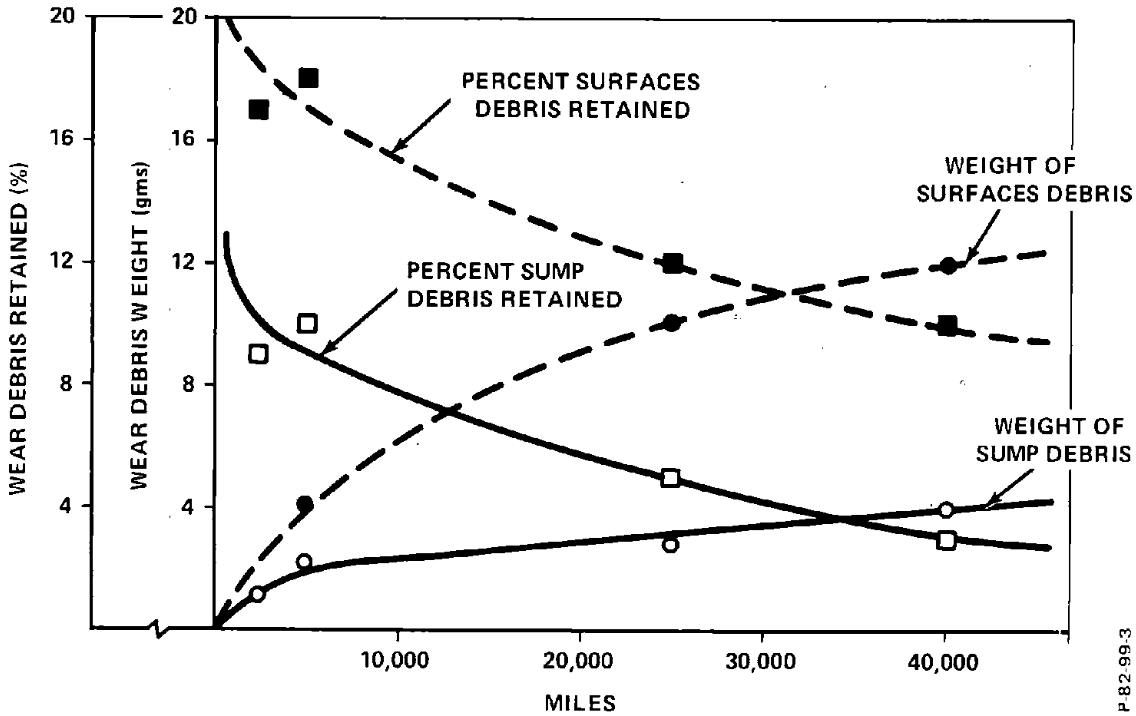

Figure 10-2 - Variation of Wear Debris Retention with Mileage (for Rear Drum Brakes)

10.3.2.1.3 Summary

As a result of the above analysis, it is proposed that the test results be weighted in the following manner for the determination of asbestos emissions distribution from a passenger vehicle:

Simulation	Test Schedule Required	Airborne (Atmosphere)	Road Drop-Out	Vehicle Retention
Disc Brake:				
New friction couple	Burnish	0.04	0.85	0.11
After 2632 miles	Composite	0.07	0.91	0.03
After 8100 miles	Composite	0.06	0.93	0.01
After 20,000 miles	Composite	0.06	0.93	0.01
Drum Brake:				
New friction couple	Burnish	0.01	0.54	0.35
After 2632 miles	Composite	0.02	0.72	0.26
After 20,000 miles	Composite	0.02	0.79	0.19

10.3.2.2 Severity Weighting Factors

10.3.2.2.1 New Versus Burnished Friction Materials

The vehicle test results indicated that rerunning the rear drum linings from vehicle test 1 on vehicle test 2 gave lower asbestos emissions. The A. B. Baseline and Detroit Traffic schedules of vehicle test 2 showed lower asbestos than the corresponding schedules of vehicle test 1. The same trends were shown for the clutch. Consequently, it is necessary to include a certain percentage (weight) of Burnish schedule results in the calculations of total asbestos emissions.

Burnish tends to be completed after approximately 200 miles of test driving schedules, but stability of surface finish may not occur until somewhat later on private passenger cars. Assuming that the maximum is 400 miles and that the brake friction materials have a 30,000-mile average life, the fraction of driving is:

$$\frac{400}{30,000} = 0.013$$

This is the severity factor used for determining the extent of Burnish asbestos emissions. During the next period of driving, the friction materials are still moving toward their stabilized level for light to moderate duty. The test vehicle used approximately 350 miles. Assuming that up to 400 miles are required, the fraction of driving is kept the same as for the Burnish factor above. Thus the A. B. Baseline factor is also 0.013.

10.3.2.2.2 Severe or Abusive Braking

The results presented previously show conclusively that total emissions increase during and immediately after severe (abusive) braking (the fade tests). While it is necessary to test brakes under these abusive conditions so that they will function in emergencies, it is not common to operate vehicles in the abusive manner that generates high emissions. Data reported in Section 10.2 indicate that severe braking occurs less than 10 percent of the time, nationwide.

Most of the severe braking takes place in comparatively remote or lightly populated mountain areas where 11.5 percent of all driving takes place (Table 10-10). With experience, most of the local drivers tend to drive in a manner where they refrain from fading the brakes. Assuming that the severe braking encountered under these conditions occurs a maximum of 10 percent, the fraction for severe braking can thus be calculated:

$$0.10 \times 11.5 = 1.15 \text{ percent of all driving}$$

The amount of hot-rodding followed by severe braking, is not known. Nor is the amount of driving known when a foot is kept on the brake at all times. A further action which causes emissions caused by severe brake friction material dragging is on the unreleased emergency brake. To account for all of these actions, the above fraction of driving should be increased to a 2.0 percent maximum. Thus the factor for the 10-Stop Fade consideration is 0.020.

10.3.2.2.3 Renewal of Friction Surfaces

The data given in Section 9.6 show that the wear rate of friction materials is increased after high-temperature operation. Consequently, the calculations of asbestos emissions requires the inclusion of an A. F. Baseline contribution. The test vehicle used approximately 350 miles; under less than moderate duty, approximately 600 miles would be required. The fraction of driving which gives the A. F. Baseline factor can be calulated:

$$\frac{600}{30,000} = 0.020$$

10.3.2.2.4 Normal Brake Operation

Most braking takes place under normal or low temperatures (less than 300°F). As indicated earlier, the Detroit Traffic Test is an accelerated vehicle test and is more severe than normal driving throughout most of the country. The temperatures actually encountered would be typical of warmer climates and hilly areas such as those found in the Los Angeles area. In any event, the Detroit Traffic Test used in this program gives the maximum asbestos emissions expected for normal brake operation.

10.3.2.3 Summary

As a result of the above analysis, it is proposed that the test results be weighted in the following manner for the determination of maximum total asbestos emissions for a passenger vehicle:

Simulation	Test Schedule Required	Weighting Factor
New friction couple	Burnish	0.013
Surfaces preparation	A. B. Baseline	0.013
Moderate braking	Detroit Traffic	0.934*
Severe braking	10-Stop Fade	0.020
Renewal of friction surfaces	A. F. Baseline	0.020

*Determined by difference

10.3.3 Asbestos Emissions Per Vehicle

10.3.3.1 Total Asbestos Emissions Estimate

The total asbestos emissions for the test vehicle can be estimated from the test results given in Section 9 and the severity weighting factors. The calculation is summarized in Table 10-19. The asbestos emissions for the disc brakes, drum brakes, and clutch from each vehicle test were averaged and used with the Burnish, A. B. Baseline, Detroit Traffic, 10-Stop Fade, and A. F. Baseline schedules. The corresponding severity factors were used to calculate the weighted emissions. The sum of the weighted emissions is the total asbestos emissions expected from an average vehicle.

10.3.3.2 Asbestos Emissions and Their Fate

The total asbestos emissions per vehicle as calculated above, are not merely deposited onto the ground or entirely emitted into the atmosphere. In general, the asbestos emissions can and will probably end up in any of three different places:

- retained in the brake and/or disposed of during servicing.
- deposited on the ground
- floated into the atmosphere

The calculation given in Table 10-20 shows that the largest part of the asbestos emissions produced is emitted from the brakes and clutch as drop-out material. The fate of the total emissions calculated earlier for the test vehicle is as follows:

Road-dropout:	23.34/28.51 x 100 = 81.9 percent
Airborne:	1.05/28.51 x 100 = 3.7 percent
Retained in Brake:	28.51 - 24.39/28.51 x 100 = 14.4 percent

10.4 ESTIMATED ASBESTOS EMISSIONS

10.4.1 Passenger Vehicles

10.4.1.1 Total Asbestos Emissions

The estimated total asbestos emissions per year can be calculated from the following information:

Total asbestos emissions per vehicle:	28.51 micrograms/mile
Number of miles per year:	9,978
Number of passenger vehicles:	96,400,000

Estimated asbestos emissions in pounds per year

$$= \frac{28.51\ \mu g}{\text{mile-vehicle}} \times 10^{-6} \frac{gm}{\mu g} \times 9.978 \times 10^{3} \frac{\text{miles}}{\text{yr}} \times \frac{1\ lb}{454\ gm} \times 96.4 \times 10^{6} \text{ vehicles}$$

= 60,400 pounds per year.

10.4.1.2 Distribution of Asbestos Emissions

The distribution of the total asbestos emissions calculated for the test vehicle can be determined by applying the percent distributions given in Section 10.3.3.2. The fate of the 60,400 pounds

Table 10-19 - Total Asbestos Emissions Calculated From the Test Vehicle (Average for the Three Vehicle Tests)

Schedule	Friction Couple	Asbestos Emissions (μg/mile)					Severity Weighting Factors	Weighted Emissions (μg/mile)
		Vehicle Test			Average	Per Axle		
		1	2	3				
Burnish	Disc Brake	16.70	36.35	7.21	20.09	40.18	0.013	0.52
	Drum Brake	59.09	24.43	11.67	31.39	62.78		0.82
	Clutch	--	--	--	1.11	--		0.01
A. B. Baseline	Disc Brake	2.23	4.71	1.96	2.97	5.94	0.013	0.07
	Drum Brake	9.22	2.38	1.98	4.52	9.04		0.12
	Clutch	--	--	--	1.11	--		0.01
Detroit Traffic	Disc Brake	2.35	12.75	0.48	5.19	10.38	0.934	9.70
	Drum Brake	11.07	5.50	0.63	5.73	11.46		10.70
	Clutch	--	--	--	1.11	--		1.03
10-Stop Fade	Disc Brake	100.60	79.13	8.82	62.80	125.60	0.020	2.51
	Drum Brake	22.58	146.14	5.03	58.15	116.30		2.33
	Clutch	--	--	--	1.11	--		0.02
A. F. Baseline	Disc Brake	29.61	6.69	3.51	13.27	26.54	0.020	0.53
	Drum Brake	5.21	3.28	0.32	2.94	5.88		0.12
	Clutch	--	--	--	1.11	--		0.02
							Total	28.51

Table 10-20 - Distribution-Weighted Asbestos Emissions From the Test Vehicle

Schedule	Friction Couple	Asbestos Emissions (µg/mile) Vehicle Test 1	2	3	Average	Per Axle	Dist. Weighting Factors Drop-Out	Airborne	Severity Weighting Factors	Weighted Emissions (µg/mile) Drop-Out	Airborne
Burnish	Disc Brake	16.70	36.35	7.21	20.09	40.18	0.85	0.04		0.44	0.02
	Drum Brake	59.09	24.43	11.67	31.39	62.78	0.54	0.01	0.013	0.44	0.01
	Clutch	-	-	-	1.11	-	0.10	0.01		0.00	0.00
A.B. Baseline	Disc Brake	2.23	4.71	1.96	2.97	5.94	0.85	0.04		0.06	0.00
	Drum Brake	9.22	2.38	1.98	4.52	9.04	0.54	0.01	0.013	0.07	0.00
	Clutch	-	-	-	1.11	-	0.10	0.01		0.00	0.00
Detroit Traffic	Disc Brake	2.35	12.75	0.48	5.19	10.38	0.93	0.06		9.02	0.58
	Drum Brake	11.07	5.50	0.63	5.73	11.46	0.79	0.02	0.934	8.45	0.21
	Clutch	-	-	-	1.11	-	0.10	0.01		0.10	0.01
10-Stop Fade	Disc Brake	100.60	79.13	8.82	62.80	125.60	0.93	0.06		2.33	0.15
	Drum Brake	22.58	146.14	5.03	58.15	116.30	0.79	0.02	0.020	1.84	0.04
	Clutch	-	-	-	1.11	-	0.10	0.01		0.00	0.00
A.F. Baseline	Disc Brake	29.61	6.69	3.51	13.27	26.54	0.93	0.06		0.49	0.03
	Drum Brake	5.21	3.28	0.32	2.94	5.88	0.79	0.02	0.020	0.10	0.00
	Clutch	-	-	-	1.11	-	0.10	0.01		0.00	0.00
									Total	23.34	1.05

calculated for the test vehicle is as follows:

Road-dropout:	49,470 pounds
Airborne:	2,230 pounds
Brake retention:	8,700 pounds

10.4.2 Trucks and Buses

10.4.2.1 Estimated Severity Factors

Truck brakes usually tend to operate at higher temperatures than passenger cars. Thus a greater proportion of high-temperature use in severity weighting can be obtained by using a larger fraction of the 10-Stop Fade asbestos emissions. For trucks and buses, the test results are arbitrarily weighted as follows:

Simulation	Test Schedule	Weighting Factor
Light Truck:		
New materials	Burnish	0.013
Moderate braking	A. B. Baseline	0.013
Moderate braking	Detroit Traffic	0.874
Abusive braking	10-Stop Fade	0.050
Surface renewal	A. F. Baseline	0.050
Medium Truck and Bus:		
New materials	Burnish	0.013
Moderate braking	A. B. Baseline	0.013
Moderate braking	Detroit Traffic	0.774
Abusive braking	10-Stop Fade	0.100
Surface renewal	A. F. Baseline	0.100
Heavy Truck:		
New materials	Burnish	0.013
Moderate braking	A. B. Baseline	0.013
Moderate braking	Detroit Traffic	0.674
Abusive braking	10-Stop Fade	0.150
Surface renewal	A. F. Baseline	0.150

10.4.2.2 Estimated Emissions Factors

In addition to the severity factors, it is necessary to estimate the total average asbestos emissions for a light truck, a medium truck (or bus), and a heavy truck. The value for the test car was 28.51 micrograms/mile. Assuming that light trucks have a result proportional to the ratio of the friction materials weights, the asbestos emissions for light trucks are larger than the test car by the following factors:

Front drum brake:	2.0
Rear drum brake:	3.0
Clutch:	2.0

A slightly larger factor is selected for the clutch as it is used more often in trucks than in passenger cars.

Following the same line of reasoning, the asbestos emissions for medium trucks and buses are larger than the test car by the following factors:

Front drum brake:	3.0
Rear drum brake:	10.0
Clutch:	4.0

The factors for a heavy truck are as follows:

Front drum brake:	5.0
Rear drum brake:	30.0
Clutch:	6.0

10.4.2.3 Calculations of Total Asbestos Emissions for Trucks and Buses

The estimates for the total average asbestos emissions per vehicle are shown in Tables 10-21, 10-22, and 10-23, for a light truck, a medium truck or bus, and a heavy truck, respectively.

Table 10-21 - Estimate for Total Asbestos Emissions Expected for a Light Truck

Schedule	Friction Couple	Asbestos Emissions Estimate Per Axle (μg/mile)	Asbestos Emissions (μg/mile)	Severity Weighting Factors	Weighted Emissions (μg/mile)
Burnish	Front Drum Brake	62.78 x 2.0	125.56	0.013	1.63
	Rear Drum Brake	62.78 x 3.0	188.34		2.45
	Clutch	1.11 x 2.0	2.22		0.03
A. B. Baseline	Front Drum Brake	9.04 x 2.0	18.08	0.013	0.24
	Rear Drum Brake	9.04 x 3.0	27.12		0.35
	Clutch	1.11 x 2.0	2.22		0.03
Detroit Traffic	Front Drum Brake	11.46 x 2.0	22.92	0.874	20.03
	Rear Drum Brake	11.46 x 3.0	34.38		30.05
	Clutch	1.11 x 2.0	2.22		1.94
10-Stop Fade	Front Drum Brake	116.30 x 2.0	232.60	0.050	11.63
	Rear Drum Brake	116.30 x 3.0	348.90		17.44
	Clutch	1.11 x 2.0	2.22		0.11
A. F. Baseline	Front Drum Brake	5.88 x 2.0	11.76	0.050	0.59
	Rear Drum Brake	5.88 x 3.0	17.64		0.88
	Clutch	1.11 x 2.0	2.22		0.11
				Total	87.51

Table 10-22 - Estimate of Total Asbestos Emissions Expected for a Medium Truck

Schedule	Friction Couple	Asbestos Emissions Estimate Per Axle (μg/mile)	Asbestos Emissions (μg/mile)	Severity Weighting Factors	Weighted Emissions (μg/mile)
Burnish	Front Drum Brake	62.78 x 3.0	188.34	0.013	2.45
	Rear Drum Brake	62.78 x 10.0	627.80		8.16
	Clutch	1.11 x 4.0	4.44		0.06
A. B. Baseline	Front Drum Brake	9.04 x 3.0	27.12	0.013	0.35
	Rear Drum Brake	9.04 x 10.0	90.40		1.18
	Clutch	1.11 x 4.0	4.44		0.06
Detroit Traffic	Front Drum Brake	11.46 x 3.0	34.38	0.774	26.61
	Rear Drum Brake	11.46 x 10.0	114.60		88.70
	Clutch	1.11 x 4.0	4.44		3.44
10-Stop Fade	Front Drum Brake	116.30 x 3.0	348.90	0.100	34.89
	Rear Drum Brake	116.30 x 10.0	1163.00		116.30
	Clutch	1.11 x 4.0	4.44		0.44
A. F. Baseline	Front Drum Brake	5.88 x 3.0	17.64	0.100	1.76
	Rear Drum Brake	5.88 x 10.0	58.80		5.88
	Clutch	1.11 x 4.0	4.44		0.44
				Total	290.72

Table 10-23 - Estimate of Total Asbestos Emissions Expected for a Heavy Truck

Schedule	Friction Couple	Asbestos Emissions Estimate Per Axle (μg/mile)	Asbestos Emissions (μg/mile)	Severity Weighting Factors	Weighted Emissions (μg/mile)
Burnish	Front Drum Brake	62.78 x 5.0	313.90	0.013	4.08
	Rear Drum Brake	62.78 x 30.0	1883.40		24.48
	Clutch	1.11 x 6.0	6.66		0.09
A. B. Baseline	Front Drum Brake	9.04 x 5.0	45.20	0.013	0.59
	Rear Drum Brake	9.04 x 30.0	271.20		3.52
	Clutch	1.11 x 6.0	6.66		0.09
Detroit Traffic	Front Drum Brake	11.46 x 5.0	57.30	0.674	38.62
	Rear Drum Brake	11.46 x 30.0	343.80		231.72
	Clutch	1.11 x 6.0	6.66		4.49
10-Stop Fade	Front Drum Brake	116.30 x 5.0	581.50	0.150	87.22
	Rear Drum Brake	116.30 x 30.0	3489.00		523.35
	Clutch	1.11 x 6.0	6.66		1.00
A. F. Baseline	Front Drum Brake	5.88 x 5.0	29.40	0.150	4.41
	Rear Drum Brake	5.88 x 30.0	176.40		26.46
	Clutch	1.11 x 6.0	6.66		1.00
				Total	951.12

Table 10-24 - Distribution-Weighted Asbestos Emissions From A Light Truck

Schedule	Friction Couple	Severity Weighted Emissions (mg/mile)	Distribution Weighting Factors			Weighted Emissions (mg/mile)		
			Drop-out	Airborne	Retention	Drop-out	Airborne	Retention
Burnish	Front Drum Brake	1.63	0.89	0.02	0.09	1.45	0.03	0.15
	Rear Drum Brake	2.45	0.89	0.02	0.09	2.18	0.05	0.22
	Clutch	0.03	0.10	0.02	0.88	0.00	0.00	0.03
A.B. Baseline	Front Drum Brake	0.24	0.90	0.03	0.07	0.22	0.01	0.02
	Rear Drum Brake	0.35	0.90	0.03	0.07	0.32	0.01	0.02
	Clutch	0.03	0.10	0.02	0.88	0.00	0.00	0.03
Detroit Traffic	Front Drum Brake	20.03	0.90	0.03	0.07	18.03	0.60	1.40
	Rear Drum Brake	30.05	0.90	0.03	0.07	27.05	0.90	2.10
	Clutch	1.94	0.10	0.02	0.88	0.19	0.04	1.71
10-Stop Fade	Front Drum Brake	11.63	0.90	0.03	0.07	10.47	0.35	0.81
	Rear Drum Brake	17.44	0.90	0.03	0.07	15.70	0.52	1.22
	Clutch	0.11	0.11	0.02	0.88	0.01	0.00	0.10
A.F. Baseline	Front Drum Brake	0.59	0.90	0.03	0.07	0.53	0.02	0.04
	Rear Drum Brake	0.88	0.90	0.03	0.07	0.79	0.03	0.06
	Clutch	0.11	0.10	0.02	0.88	0.01	0.00	0.10
		87.51				76.95	2.56	8.01

Table 10-25 - Summary of All Brake and Clutch Emission (lbs per year)

Vehicle	Number of Vehicles	Total Asbestos Emissions	Distribution		
			Drop-Out	Airborne	Brake Retention
Passenger Cars	96,400,000	60,400	49,470	2,230	8,700
Light Trucks	17,100,000	32,300	28,420	940	2,940
Medium Trucks and Buses	2,600,000	16,300	14,330	470	1,500
Heavy Trucks	1,200,000	32,900	28,920	950	3,030
Miscellaneous*	6,615,000	16,300*	14,330	470	1,500
	Totals	158,200	135,470	5,060	17,670
	Percent of Total		(85.6)	(3.2)	(11.2)

*Estimated equal to medium trucks as weights of friction material used for both categories are almost equal (Table 12). Includes motorcycles, trailers, etc.

The estimated total asbestos emissions per year for light trucks can be calculated from the following information:

Total asbestos emissions per vehicle:	87.51 μg/mile
Number of miles per year:	9,807
Number of trucks:	17,100,000

Estimated asbestos emissions in pounds per year

$$= 87.51 \frac{\mu g}{mile} \times 10^{-6} \frac{gm}{\mu g} \times 9.807 \times 10^{3} \frac{miles}{yr} \times \frac{1\ lb}{454\ gms} \times 17.1 \times 10^{6}\ vehicles$$

= 32,300 pounds per year

The estimated total asbestos emissions per year for medium trucks and buses can be calculated from the following information:

Total asbestos emissions per vehicle:	290.72 μg/mile
Number of miles per year:	9,807
Number of trucks:	2,600,000

Estimated asbestos emissions in pounds per year

$$= 290.72 \frac{\mu g}{mile} \times 10^{-6} \frac{gm}{\mu g} \times 9.807 \times 10^{3} \frac{miles}{yr} \times \frac{1\ lb}{454\ gms} \times 2.60 \times 10^{6}\ vehicles$$

= 16,300 pounds per year

The estimated total asbestos emissions per year for heavy trucks can be calculated from the following information:

Total asbestos emissions per mile:	951,12 μg/mile
Number of miles per year:	9,807
Number of trucks:	1,600,000

Estimated asbestos emissions in pounds per year

$$= 951.12 \frac{\mu g}{mile} \times 10^{-6} \frac{gm}{\mu g} \times 9.807 \times 10^{3} \frac{miles}{yr} \times \frac{1\ lb}{454\ gms} \times 1.60 \times 10^{6}\ vehicles$$

= 32,900 pounds per year

10.4.2.4 Total Truck Asbestos Emissions

The estimated value for the total asbestos emissions from trucks and buses is as follows:

Light trucks	32,300 pounds
Medium trucks and buses	16,300 pounds
Heavy trucks	32,900 pounds
	81,500 pounds

10.4.2.5 Distribution of Truck Asbestos Emissions

10.4.2.5.1 Estimated Distribution Weighting Factors

The distribution weighting factors for passenger car brakes are discussed in Section 10.3.2.1. Trucks contain drum brakes which are designed to be more open than passenger car drum brakes. In many instances, no splash shields are used or they are very open. Moreover, trucks run with hard tires and stiff suspensions; these lead to a hard ride and more shaking at the wheels. Consequently, the retention of wear debris in truck drum brakes is estimated to be approximately 25 percent of that for passenger vehicle drum brakes.

From the data given in Section 10.3.2.1.3, it is possible to estimate the following distribution weighting factors for truck drum brakes:

Simulation	Test Schedule	Airborne	Road Drop-Out	Vehicle Retention
New friction couple	Burnish	0.02	0.89	0.09
After 2632 miles	Composite	0.03	0.90	0.07

The airborne figure was adjusted upward. The openness of the disc brake gives rise to a higher airborne fraction than for a closed drum brake. The value estimated for the truck drum brake takes this into account.

10.4.2.5.2 Truck Asbestos Emissions and Their Fate

The total asbestos emissions calculated for the light truck, medium truck and bus, or heavy truck will be distributed into three places:

- retained in the brake and/or disposed of during service
- deposited on the ground
- floated into the atmosphere

The typical calculations for the light trucks are given in Table 10-24 and can be summarized:

Road Drop-out:	76.95/87.51 x 100 = 87.9 percent
Airborne:	2.56/87.51 x 100 = 2.9 percent
Brake Retention:	8.01/87.51 x 100 = 9.2 percent

10.4.3 Estimated Asbestos Emissions

The summary of the total asbestos emissions estimates and their distribution is given in Table 10-25.

Table 10-26 - Calculation of Weighted Average Unconverted Asbestos Percent for Sump Sample

Schedule	Vehicle Test	Front Brake	Rear Brake	Overall Average	Weighting Factor	Weighted Percent
Burnish	1 2 3 Average	0.813 0.402 0.218 0.478	- 0.484 0.063 0.274	0.376	0.013	0.005
A.B. Baseline	1 2 3 Average	1.650 0.236 0.106 0.664	0.179 0.268 0.063 0.170	0.417	0.013	0.005
Detroit Traffic	1 2 3 Average	0.247 0.304 0.018 0.190	0.129 0.240 0.046 0.138	0.164	0.824	0.135
10-Stop Fade	1 2 3 Average	0.463 0.244 0.045 0.251	0.280 0.199 0.102 0.194	0.223	0.075	0.017
A.F. Baseline	1 2 3 Average	0.656 0.443 0.158 0.419	0.419 0.138 0.034 0.197	0.308	0.075	0.023
						0.185

Table 10-27 - Calculation of Weighted Average Asbestos Percent for Surfaces Sample

Schedule	Vehicle Test	Front Brake	Rear Brake	Overall Average	Weighting Factor	Weighted Percent
Burnish	1 2 3 Average	0.398 0.968 0.101 0.489	0.865 1.416 0.046 0.776	0.633	0.013	0.008
A.B. Baseline	1 2 3 Average	0.472 0.311 0.024 0.269	0.415 0.098 0.056 0.190	0.230	0.013	0.003
Detroit Traffic	1 2 3 Average	0.137 0.548 0.013 0.233	0.373 0.113 0.057 0.181	0.207	0.824	0.171
10-Stop Fade	1 2 3 Average	0.162 0.261 0.041 0.155	0.071 0.619 0.055 0.248	0.202	0.075	0.015
A.F. Baseline	1 2 3 Average	0.507 0.173 0.073 0.251	0.242 0.237 0.022 0.167	0.209	0.075	0.016
						0.213

10.4.4 Alternate Estimate for Total Asbestos Emissions

An alternate method to calculate an estimate for total asbestos emissions is proposed.

Tables 10-26, 10-27, and 10-28 list the data and the calculations required to produce a weighted average asbestos percent for the sump, surfaces, and airborne samples using the weighted portions of the Baseline, A. B. Baseline, Detroit Traffic, 10-Stop Fade, and A. F. Baseline schedules.

The data given in Table 10-16 indicated that the percentages of annual consumption of friction materials is as follows:

Passenger Car Brakes: 56 percent
Truck Brakes: 44 percent

The data given in Section 10.3.2.1.3 and Section 10.4.2.5.1 show that the average distributions for most of the brake mileages can be summarized as follows:

Brake	Airborne	Road Drop-Out	Vehicle Retention
Passenger Car Brakes	0.03	0.77	0.20
Truck Brakes	0.03	0.90	0.07

The calculation for the weighted average asbestos found in all brakes is given in Table 10-29.

The average wear debris recovery for each vehicle can also be calculated from the data given in Table 9-14:

	Fronts	Rears
Test 1	51.2*	67.8*
2	60.8	81.6
3	60.2	81.3

*Low because of incomplete, difficult recoveries of Fade samples.

The drum rear samples are known to contain approximately 10 weight percent material such as iron oxide from drum wear. Thus an average recovery of approximately 65 percent, based on the debris from the friction materials for vehicle tests 2 and 3, is used in the calculation. Therefore, the asbestos percent based on the friction material worn in the test vehicle is calculated as follows:

$$0.206 \times 0.65 = 0.134$$

Table 10-28 - Calculation of weighted average asbestos Percent for Airborne Samples

Schedule	Vehicle Test	Front Brake	Rear Brake	Overall Average	Weighting Factor	Weighted Percent
Burnish	1	0.144	0.349			
	2	0.186	0.087			
	3	0.099	0.060	0.154	0.013	0.002
	Average	0.143	0.165			
A.B. Baseline	1	0.290	0.493			
	2	0.211	0.344			
	3	0.125	0.044	0.251	0.013	0.003
	Average	0.209	0.294			
Detroit Traffic	1	0.052	0.092			
	2	0.234	0.115			
	3	0.025	0.037	0.093	0.824	0.077
	Average	0.104	0.081			
10-Stop Fade	1	0.154	0.132			
	2	0.107	0.194			
	3	0.055	0.014	0.109	0.075	0.008
	Average	0.105	0.113			
A.F. Baseline	1	0.134	0.079			
	2	0.165	0.180			
	3	0.047	0.003	0.101	0.075	0.008
	Average	0.115	0.087			
						0.098

Table 10-29 - Data and Calculation of Weighted Asbestos Percent for All Vehicles

Friction Materials	Fraction of Friction Material	Fraction of Debris		Weight Percent Asbestos	Weighted Asbestos Percent
Passenger Car	0.56	Airborne	0.03	0.098	0.002
		Drop-Out	0.77	0.213	0.092
		Retention	0.20	0.185	0.021
Truck	0.44	Airborne	0.03	0.098	0.001
		Drop-Out	0.40	0.213	0.084
		Retention	0.07	0.185	0.006
					0.206

The total weight of friction material worn away annually in brakes is 117 million pounds. The total asbestos estimate from brakes can now be calculated:

$$117{,}000{,}000 \times 0.00134 = 157{,}000 \text{ pounds}$$

The total weight of friction material worn away annually in clutches is 6.6 million pounds. The total asbestos estimate from clutches (assuming a retention of ∿75 percent) can be calculated as follows:

$$6{,}600{,}000 \times 0.00047 \times 0.25 = 800 \text{ pounds}$$

Thus the total is approximately 157,800 pounds, which agrees with the figure reported in Section 10.4.3 above.

10.5 SUMMARY OF ASBESTOS EMISSIONS

The results indicate that more than 99.7 percent of the asbestos used in friction material is converted to a non-fibril form. The total asbestos emissions for all vehicles in the United States is estimated to be 158,000 pounds annually. Of this total, a small part was found to remain airborne. The contribution to the atmosphere is estimated to be 5060 pounds, or 3.2 percent of the total asbestos emissions.

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SECTION 11

SUMMARY

The specific objectives of this program were stated earlier. The end objective was the documentation of asbestos emissions from brakes and clutches and the assessment of their overall contributions to the atmosphere. These objectives were met by means of the program as planned and completed.

For the results to be representative of average consumer-type vehicle usage, a vehicle intermediate between compacts and luxury vehicles was selected. The vehicle was equipped with front disc brakes, rear drum brakes, and a dry clutch. All friction material used contained asbestos. Three vehicle tests were run. The first vehicle test was run with the original-equipment friction materials. The second vehicle test simulated a partial reline - fronts only relined - while the rears were repeated to give a replicate test, and an indication of emissions trends for friction materials with continued use. The third vehicle test simulated a complete brake reline, and included turned discs and drums. The friction materials selected for the program were representative of those supplied by the industry - five different manufacturers produced the original equipment and aftermarket disc pads and drum linings, which were selected in part because of their high-volume usage.

The collection of particulate and gaseous emissions from any vehicle friction couple has never, to the authors' knowledge, been reported in the literature. To define the extent of these emissions, a collection system was devised which combined the functions of separation and storage. Unique emissions collectors for both disc and drum brakes, and for a clutch, were conceived, designed, and built as the main embodiment of this instrumentation. The collectors separated the wear debris into three different fractions: a sump sample which included the wear debris on the lining surfaces, in the rivet holes, and on the brake drum; a surfaces sample which included the wear debris on the brake and collector shroud surfaces; and an airborne sample collected on membrane filters.

The front disc brake emission collector was tested on an inertia dynamometer to check out its operation. The most critical part of the collector operation was the rotating seal. The final design selected was made from graphite-filled Teflon which rotated against a hardened steel ring. Thermal response tests were made, the results indicating that for normal operation the shrouded disc brake would operate at a slightly higher temperature than the normal brake configuration. A method was devised to determine the leak rate of the collector. The rotating seal was largely responsible for the residual leak; the leak rate was reduced significantly by use of a very small amount of high-temperature grease. The rotating seal underwent durability testing and

survived seven hours at 50 mph. A second series of dynamometer tests gave reproducible emissions and temperatures. Finally, a test was made in which the collector, and especially the rotating seal, were shown to be relatively leak-tight to external liquid and particulate contaminants.

The vehicle was equipped with standard brake test instrumentation. A front disc brake collector and a rear drum brake collector were installed on the right side of the vehicle. The clutch was sealed by closing the few holes in its casing. The left wheel brakes were left in their normal configuration and were used to monitor the operation of the shrouded brakes. Wear debris was taken from the left brakes as well as from those on the right. The amounts of debris formed and their compositions were used to demonstrate that the brake shrouding did not significantly affect the operation of the brakes on the right side.

Although there are many brake and friction material tests suitable for measuring a specific condition or combination of conditions, no one test adequately matches driving conditions which would be representative of all vehicles. Consequently, it became necessary to devise a rational and meaningful vehicle test. Seven schedules were chosen, and each was followed by a measurements procedure (take emissions samples, measure wear, inspect the systems, and replace worn parts). The first three schedules - Burnish, After Burnish (A.B.) Baseline, and Detroit Traffic - constituted low to moderate temperature testing. The final four schedules - 10-Stop Fade, After Fade (A.F.) Baseline, 15-Stop Fade, and Final Baseline - constituted high temperature and abusive testing.

A detailed step-by-step procedure was prepared for the removal of brake emissions from the collectors. The amounts of debris collected at the various locations were used later to calculate the mass balances. A detailed step-by-step procedure was also prepared for the sampling, handling, and analysis of the asbestos emissions.

The analysis of brake wear debris indicated the presence of 20-30 weight percent polymeric and carbonaceous material, which in turn produced a fluffy appearance when the material was examined in the scanning electron microscope. The organic portion was therefore removed by low temperature ashing. Two representative samplings were used: the first in sample selection for low temperature ashing; and the second in sample selection for distribution on a filter membrane for subsequent analysis.

The only suitable method of analysis for asbestos was microscopy. At the beginning of the program, one optical and three transmission electron microscopy methods had been developed by others. Two of the electron microscope methods were not suitable because they changed the fiber size distribution of the asbestos. Initial experiments indicated that the asbestos in wear debris varied in size from 0.1 micron in diameter up to 2.0 microns in diameter by 50 microns in length. To preserve the particle size distribution, a combination of optical microscopy and transmission electron microscopy was selected. Optical microscopy with phase contrast optics at 400 diameters was used to detect fibers with diameters of 0.5 micron and above. Transmission electron microscopy at 22,000 diameters was used to detect fibers with diameters of 0.5 micron and below.

The projected fiber diameter and length were used to determine the fiber volume. The volumes were summed, converted to weight, and normalized for the entire sample weighed onto the filter. A computer program was subsequently developed to minimize computational time and to eliminate errors in the processing of these calculations.

The possible sources of error associated with sample processing and analysis were minimized through the use of statistical methods. The largest effect found on the asbestos analysis was the occasional occurrence of a large fiber. The extent of error increased as the percent asbestos in the sample decreased. The data showed that the maximum deviation for results with asbestos contents above 0.10 percent averaged 12-15 percent and had a maximum at approximately 20 percent. The maximum deviation increased for asbestos contents below 0.10 percent, where errors for the small amounts of asbestos emissions become less significant from the standpoint of air pollution.

A gas handling system was set up to separate, measure, and transfer samples to the gas chromatograph. A step-by-step procedure was prepared. The non-condensable gases were analyzed by separating the gases on a Porapak Q column and then detecting the separated components with a thermal conductivity detector. In some instances, a flame ionization detector was also used. The condensable gases were analyzed by separating the components on a W-98 silicone gum rubber column and detecting with a flame ionization detector.

The vehicle tests were carried out during the period May 1 to November 17, 1972. Only one major problem occurred during the vehicle testing: during the 10-Stop Fade of vehicle test 1, the hardened steel ring, on which the rotating seal slides, became loose. The ring was re-anchored and no further problem was encountered during the 15-Stop Fade or in any further test schedule. This result showed the durability of the collector and rotating seal design and construction. For the 8100 miles of testing, only seven front and eight rotating seals were required. This was better than anticipated at the start of the program. The mileage accumulations for each schedule of each vehicle test showed that the mileages were reproducible.

Prior to vehicle test 1, a Burnish schedule was performed and the temperature for the right front disc brake was found to be near 400°F. The temperature difference, ΔT, between the right and left front brakes was 200-250°F. This was unacceptable. The addition of several thermal control aids reduced the difference to the range 115 to 160°F. Most important was the reduction of the right front brake operating temperatures from about 400°F to about 300°F. The brake shrouding did not present any problems on hot days. During the Detroit Traffic Test, the ΔT between the front brakes remained between 100 and 140°F while that for the rear drum brake remained between 10 and 30°F.

During the fade tests, the right front brake was programmed according to known temperature versus stop-number curves obtained for the same friction materials previously run on an inertia dynamometer and on a normal test vehicle. After the seventh stop, the time increment between stops was increased to prevent the right front brake from overheating the friction materials within the shroud. The 15-Stop Fade produced an additional effect within the brake. The heat generated was retained within the shroud and caused the brake fluid within the right front caliper to heat. The resultant fluid boil produced a loss of pedal for the last two fade stops and persisted through the first eight recovery stops.

The recovery of particulate emissions from both front brakes yielded a comparison of the amounts of emissions of the normal with the shrouded disc brake. For both brakes, the sump sample appeared to reach and maintain an average amount of debris which was independent of the mileage. When the debris was removed, the steady-state value appeared to reestablish itself. The surfaces sample for the open brake showed the same behavior. The recovery data were used to calculate the distribution weighting factors used later to calculate the distribution of brake emissions in three categories: retained in the brake, released as road drop-out material, and airborne material.

The amounts of particulates collected in the three samples were compared with the friction material weight losses. In all cases, the data for the right front brake ranged from approximately 42-percent recovery in the initial schedule of each vehicle test to approximately 70 percent for the final schedules. The low initial recovery may have been caused by excess gassing during Burnish, resulting in a lower recovery of particulates. The brake emissions recovered from the fade tests were "tarry", and the surfaces samples were recovered only with difficulty.

The material recovery data for the rear brakes showed wide variation. The problem in part was due to the 80-percent sump carry-over to the following test. During certain vehicle tests, the sump sample was redistributed within the brake and registered a lower value after the test. Thus, a negative weight was recorded. The other samples for that brake did increase and a positive overall value was always recorded.

The range of asbestos content in the brake emissions for vehicle tests 1 and 2 went from a high of 1.65 percent to a low of 0.03 percent for the 90 analyses; only three were above 1.00 percent. The overall average for vehicle test 1 was 0.38 percent and for vehicle test 2 was 0.25 percent. For vehicle test 3, the range of asbestos content was from a high of 0.51 percent to a low of 0.003 percent. The overall average was 0.07 percent.

To provide a systematic independent check on the asbestos analyses, the EPA Project Officer arranged a second contract for Battelle Columbus Laboratories to analyze twenty-four samples generated during the program. Johns-Manville also provided three analyses. The Johns-Manville and

Battelle data agreed very well. In 19 of the 24 analyses, the Program results were slightly higher than the corresponding Battelle results. The Program average was 0.25 percent, while the Battelle average was 0.17 percent or 68 percent of the Program average. The Program data were expected to be higher for the following reasons: all larger fibers (bundles of fibrils) found were assumed to be cylinders of projected diameter and length, and a fiber with an elliptical cross section was actually smaller in volume than reported; and all fibers were assumed to be 100-percent asbestos (partially degraded asbestos or olivine fibers were weak and mechanically reduced to non-fibrous material by the other analytical techniques, hence only the remaining asbestos fibrils that remained were counted).

Analysis of the gaseous emissions was made difficult by the large quantities of water and carbon dixodie which by-passed the gas conditioning trap and entered through the rotating seals. Most samples showed traces of C_1 to C_3 hydrocarbons only as lower concentrations of higher molecular weight gases could not be detected. When the gases were concentrated from the fade tests, C_4 to C_8 compounds such as butanes, benzene, toluene, phenol, and cresols were detected in the gas traps. The corresponding shroud extracts showed C_{12} to C_{30} materials, including cardanol.

To compare the emissions properly, it was found necessary to calculate the asbestos emission factors for each sample in micrograms/mile. The values of these factors were obtained by multiplying the weights of brake debris generated by the appropriate asbestos percents, then dividing by the miles per test schedule. Thus, either a high asbestos content or a large sample gave a high factor. The following observations were made:

- asbestos emissions were higher for new friction surfaces and decreased with use;
- the drum brake produced more asbestos emissions than the disc brake initially, the difference decreasing as the friction materials continued in use;
- heavy (abusive) duty did not necessarily give a higher percent asbestos, however, the large amount of debris produced gave a significant rise in asbestos emissions;
- asbestos emissions from the brakes were found to decrease from fade or heavy-duty stops (highest) to burnish to moderate braking (lowest);
- for the disc pads only, there was an increase in asbestos emissions with increased asbestos content in the friction material (there was no such trend for the drum brake materials);

- both the front disc pads and the drum linings of vehicle test 3 have wear comparable to that found in the other two vehicle tests, yet the asbestos emissions were significantly lower (both pads and secondary linings contained brass chips which may have been in part responsible for the more complete conversion of the asbestos in the brake emissions); and
- for both disc and drum brakes, the surfaces sample was the largest of the three (∿92 percent), the sump sample was next (∿7 percent), and the airborne sample was the smallest (∿1 percent).

Each fade schedule included the 12-stop recovery and a 35-stop reburnish. It was expected that the recovery and reburnish stops would remove the heat-damaged rubbing surfaces of the friction materials. However, both the A.F. Baseline and Final Baselines show an average increase of 250 percent more wear over their approximately 350 miles or approximately 1500 stops. These data indicate that many stops were necessary to produce a renewed surface.

The end objective of this report was to develop the best possible estimate of total brake and clutch emissions per year for the U.S. population of braked vehicles in use. A data base was obtained from a wide variety of trade publications and from industry and government contacts. The number of vehicles given and the other data presented indicated a wide and varied usage so that some assumptions had to be made in preparing the asbestos emissions estimates.

The asbestos content in brake friction materials was given by the two most knowledgable industry sources as 90 and 120 million pounds for 1972. In the program our calculations, ∿118 million pounds was used. These ∿118 million pounds of asbestos were incorporated in 171 million pounds of brake friction materials. A calculation gave the total brake friction material worn away as 117 million pounds per year. The program calculation for the asbestos content in clutch friction materials was 4.38 million pounds in 8.76 million pounds of friction material. A calculation gave the total clutch friction material worn away as 6.56 million pounds.

Two series of weighting factors were developed. The distribution weighting factors were calculated from the material recoveries in the shrouded and unshrouded brakes as indicated earlier. Estimates were made for both disc and drum brakes from the test vehicle for the amounts of the different samples distributed from the brakes. These estimates were made for the Burnish schedule, for the end of a complete vehicle test, and for the end of all three vehicle tests. For the drum brake, estimates were made for up to 40,000 miles. The severity weighting factors were calculated from the percentages of different braking modes: for new versus burnished friction materials, for severe (or abusive) versus moderate braking, and for the renewal of friction surfaces (post-fade).

The total asbestos emissions estimate for the test vehicle was calculated from the asbestos emissions factors and the severity weighting factors. The average asbestos emissions factors for the disc brakes, drum brakes, and clutch were used along with the Burnish (new surfaces), A.B. Baseline (surfaces preparation), Detroit Traffic (moderate braking), 10-Stop Fade (severe braking) and A.F. Baseline (surface renewal) weighting factors. The value obtained for the test vehicle was 28.51 μg/mile.

The total asbestos emissions were not considered to be merely dumped onto the ground or thrown into the atmosphere. The fates of the emissions were calculated with the use of the distribution weighting factors as follows:

Road Drop-out	81.9 percent
Airborne	3.7 percent
Brake Retention	14.4 percent

The annual total asbestos emissions estimate for 96,400,000 passenger vehicles travelling an average of 9,978 miles per year was found to be 60,400 pounds distributed as follows:

Road Drop-Out	49,470 pounds
Airborne	2,230 pounds
Brake Retention	8,700 pounds
	60,400 pounds

Truck brakes usually tend to generate and to operate at higher temperatures than passenger cars. To estimate asbestos emissions for light, medium, and heavy trucks, it was found necessary to adjust the severity under which the emission would be expected to occur. The severity weighting was obtained by using a larger fraction of the 10-Stop Fade (and A.F. Baseline) asbestos emissions according to the following progression:

Passenger car	2.0 percent
Light truck	5.0 percent
Medium truck (and bus)	10.0 percent
Heavy truck	15.0 percent

In addition, it was necessary to estimate the asbestos emissions factors. Assuming that these factors were roughly proportional to the increased friction material weights of the appropriate vehicles compared to the test vehicle, the following estimated factors were determined:

	Front Drum Brake	Rear Drum Brake	Clutch
Light truck	2.0	3.0	2.0
Medium truck (and bus)	3.0	10.0	4.0
Heavy truck	5.0	30.0	6.0

The annual total asbestos emissions estimates for light trucks, medium trucks (and buses) and heavy trucks were found to be:

Light trucks	32,300 pounds
Medium trucks (and buses)	16,300 pounds
Heavy trucks	32,900 pounds
	81,500 pounds

The distribution weighting factors for trucks were calculated based on the following considerations. The truck drum brake is designed to be more open than the car drum brake and in many instances no splash shields are used. Based on the estimates, that only about 25 percent as much debris remains in a truck drum brake as compared to a passenger car drum brake, distribution weighting factors for trucks were estimated. The distribution of the total asbestos emissions estimate was as follows:

Road Drop-Out	87.9 percent
Airborne	2.9 percent
Brake Retention	9.2 percent

The summary of the estimated asbestos emissions for all vehicles in pounds/year was calculated as follows:

	Total Asbestos Emissions	Distribution		
		Drop-Out	Airborne	Retention
Passenger Cars	60,400	49,470	2,230	8,700
Light Trucks	32,300	28,420	940	2,940
Medium Trucks (and buses)	16,300	14,330	470	1,500
Heavy Trucks	32,900	28,920	950	3,030
Miscellaneous	16,300	14,330	470	1,500
	158,200	135,470	5,060	17,670
Distribution by percent:		85.6%	3.2%	11.2%

These estimates should be considered as maximum values.

The total asbestos emission estimates, and especially the airborne emissions estimate, are considerably lower than the 540,000 pounds estimated by IIT Research Institute.[10-11]

APPENDIX A

WEAR DEBRIS CALCULATIONS

A.1 INTRODUCTION

This appendix discusses friction material reactions used to estimate amounts of wear debris which were expected to have been collected during various cycles of the "Brake Emissions" program. Consideration is given to both disc and drum brakes.

A.2 FRONT DISC BRAKE

A.2.1 Composition

From previous studies, the typical composition of a disc pad can be approximated:

Resin, Cashew, Rubber	∿32 wt %
Asbestos	∿64 wt %
Zinc	∿4 wt %

A.2.2 Burnished Products

From various studies, the following amounts of burnished products can be estimated.

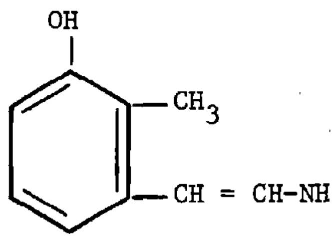
- Particulates

			Gravimetric Factor
Resin, Cashew, Rubber	∿32 wt % →	Carbonaceous Binder ∿16 wt %	0.50 (from TGA)
Asbestos	∿64 wt % →	Olivine ∿55 wt %	0.86 (from TGA)
Zinc	∿4 wt % →	ZnO ∿5 wt %	1.25 (from TGA)
	Total	76 wt %	

Consequently, the expected amount of particulate wear debris expected is 76% of the weight lost. Although disc wear does occur, it cannot be estimated at this time.

- Gaseous Products

  The average organic molecule can be assumed to have the structure:



$C_9H_{10}ON$

which undergoes the following oxidation reaction:

$$C_9H_{10}ON + 11.5\ O_2 \rightarrow 9\ CO_2 + 5\ H_2O + NO$$
$$MW = 148 \quad MW = 32$$

From the above calculation, only 50% of the organic portion oxidized:

$$32 \text{ wt } \% \times 0.50 = 16 \text{ wt } \%$$

which gives 16/148 = 0.108 mole of organic oxidized. This requires:

$$11.5 \times 0.108 = 1.24 \text{ moles of } O_2$$

$$1.24 \times 32.0 = 39.7 \text{ gms of } O_2$$

Total amount of material reacting:

$$16.0 + 39.7 = 55.7 \text{ gms}$$

Conversion factor is:

$$\frac{55.7}{16.0} = 3.48$$

Since not all 16.0 gms of the organic portion will be completely oxidized to gases, this value represents a maximum amount of material expected. The expected amount of gaseous wear products is 56% of the weight lost.

A.2.3 Typical Disc Brake Wear Rates

Burnish:	∿0.007"	or	∿0.018 cm
Detroit Traffic:	∿0.020"	or	∿0.051 cm
SAE Fade:	∿0.030"	or	∿0.076 cm
7 Stop, 90 mph:	∿0.015"	or	∿0.038 cm

A.2.4 Disc Pad Area

Inner: 8.50 in^2
Outer: 11.25 in^2

19.75 in^2

$$19.75 \text{ in}^2 \times (2.54 \text{ cm/in})^2 = 127.5 \text{ cm}^2$$

A.2.5 Calculated Wear During Burnish

Area x Thickness - 127.5 x 0.018 = 2.30 cc

Typical S.G. for disc pad is 1.70

Calculated weight loss:

$$2.30 \times 1.70 = 3.91 \text{ gms}$$

- Particulate Portion

$$3.91 \times 0.76 = 2.97 \text{ gms}$$

which will be collected in four areas:

sump
brake surfaces
8.0μ filter
0.2μ filter

- Gaseous Portion

$$3.91 \times 0.56 = 2.19 \text{ gms}$$

which will be collected in three traps:

one condensable gas trap
two noncondensable gas traps filled with charcoal

- Total Sample Expected

$$2.97 + 2.19 = 5.16 \text{ gms.}$$

A.2.6 Summary of Typical Wear Expected

Test	Wear (inch/cm)	Particulates (gms)	Gases (gms)	Total
Burnish	0.007/0.018	2.97	2.19	5.16
Detroit Traffic	0.020/0.051	8.47	6.26	14.73
SAE Fade	0.030/0.076	12.70	9.38	22.08
7 Stop, 90 mph	0.015/0.038	6.36	4.68	11.04

A.3 REAR DRUM BRAKE

A.3.1 Composition

From previous studies, the typical compositions of primary and secondary linings can be approximated:

	Primary	Secondary
Resin, Cashew	28	31
Asbestos	72	69

A.3.2 Brake Parameters

Designation: 11 x 2-1/4" DSSA

Primary Area: 2.25" x 8.8" (average arc length) = 19.8 in^2

Secondary Area: 2.25" x 11.5" (average arc length) = 25.9 in^2

higher torque stops.

(The total lining length is 8.8 + 11.5 = 20.3". The actual drum circumference is 3.14 x 11" = 34.6". Thus the lining sweeps 20.3/34.6 x 100 = 59% of the available drum surface.)

A.3.3 Burnished Products

Because the secondary is programmed to absorb more torque and essentially wear more throughout the lining combination's usage, and because the primary and secondary wear debris contributions are always combined, a more typical starting composition for the combination must be slanted toward the secondary's composition analysis:

Resin / Cashew	30 wt %
Asbestos	70 wt %

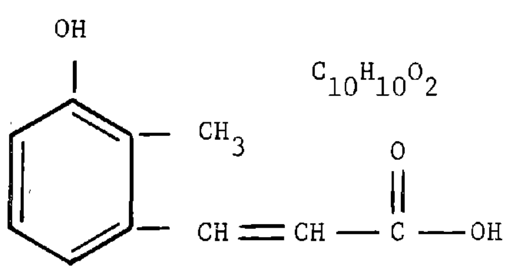
The following amounts of burnished products can be estimated:

- Particulates

			Gravimetric Factor
Resin / Cashew	30 wt % →	Carbonaceous Binder ∿15 wt %	0.50
Asbestos	70 wt % →	Olivine ∿62 wt %	0.90
		77 wt %	

- Gaseous Products

The average organic molecule can be assumed to be:



$C_{10}H_{10}O_2$

which undergoes the following oxidation reaction:

$$C_{10}H_{10}O_2 + 11.5\ O_2 \rightarrow 10CO_2 + 5H_2O$$

$$MW = 162$$

Since only 50% of the organic portion is oxidized, i.e., 15 wt %, this corresponds to 15/162 = 0.093 mole oxidized which in turn requires 11.5 x 0.093 x 32 = 34.3 gms of oxygen. The total amount of reactants is 15.0 + 34.3 = 49.3 gms which represent a gravimetric factor equal to:

$$\frac{49.3}{15.0} = 3.29$$

A.3.4 Typical Drum Rear Wear Rates

Burnish:	∿0.005"	or	∿0.013 cm
Detroit Traffic:	0.010"	or	0.026 cm
SAE Fade:	∿0.008"	or	∿0.020 cm
7 Stop, 90 mph:	0.005"	or	0.013 cm

A.3.5 Drum Brake Lining Areas

Primary:	19.8 in^2
Secondary:	25.9 in^2
	45.7 in^2

$$45.7\ in^2 \times (2.54\ cm/in)^2 = 297\ cm^2$$

A.3.6 Calculated Wear During Burnish

Volume = Area x Thickness
= 297 x 0.013
= 3.86 cc

Typical S. G. is 1.70

Calculated weight lost:

$$3.86 \times 1.70 = 6.56 \text{ gms}$$

- Particulate Portion

$$6.56 \times 0.77 = 5.15 \text{ gms}$$

- Gaseous Portion

$$6.56 \times 0.49 = 3.21 \text{ gms}$$

- Total Wear Debris

$$5.15 + 3.21 = 8.36 \text{ gms}$$

A.3.7 Summary of Typical Wear Expected

Test	Wear (inch/cm)	Particulates (gms)	Gases (gms)	Total (gms)
Burnish	0.005/0.013	5.15	3.21	8.36
Detroit Traffic	0.010/0.026	10.30	6.42	16.72
SAE Fade	0.008/0.020	8.24	5.13	13.37
7 Stop, 90 mph	0.005/0.013	5.15	3.21	8.36

APPENDIX B

NUCLEPORE FILTER FLOW CHARACTERISTICS FOR BRAKE LINING WEAR DEBRIS

B.1 INTRODUCTION

This appendix describes a series of experiments used to define the filter flow characteristics of Nuclepore membranes with varying loadings of brake lining wear debris. Figure B-1 is a schematic of the experimental setup.

B.2 FLOW VERSUS PRESSURE DROP

Table B-1 is the compilations of flow versus pressure drop data for both unloaded filters and loaded filters containing approximately 1.0 gram of wear debris (from a 1970 Chrysler Imperial rear drum brake). This data is plotted in Figure B-2.

B.3 FLOW AND PRESSURE DROP VERSUS LOADING

Table B-2 is the flow and pressure drop variations versus filter loading data at a fairly high initial pressure drop setting while Table B-3 is similar data for a lower initial pressure drop. The data are plotted in Figure B-3. The initial and final (with approximately 1 gram loading) pressure drops and flows for this data are identified as Runs 3 and 4 on Figure B-2.

B.4 MATERIAL BALANCE DATA

Additional Table B-2 Data:

• Amount of debris added to system:	1036.0 mg
Amount of debris collected on filters:	1000.6
Amount of debris lost in system*:	35.4 mg

*some spillage, most remains on walls of tube leading from funnel to filter holder.

• Removal of 8μ membrane from under debris after light shaking:	15.3 mg
Original weight:	14.1
Amount remaining on filter:	1.2 mg

• Removal of 8μ membrane from under debris and air blow:	14.7 mg
Original weight:	14.1
Amount remaining on filter:	0.6 mg

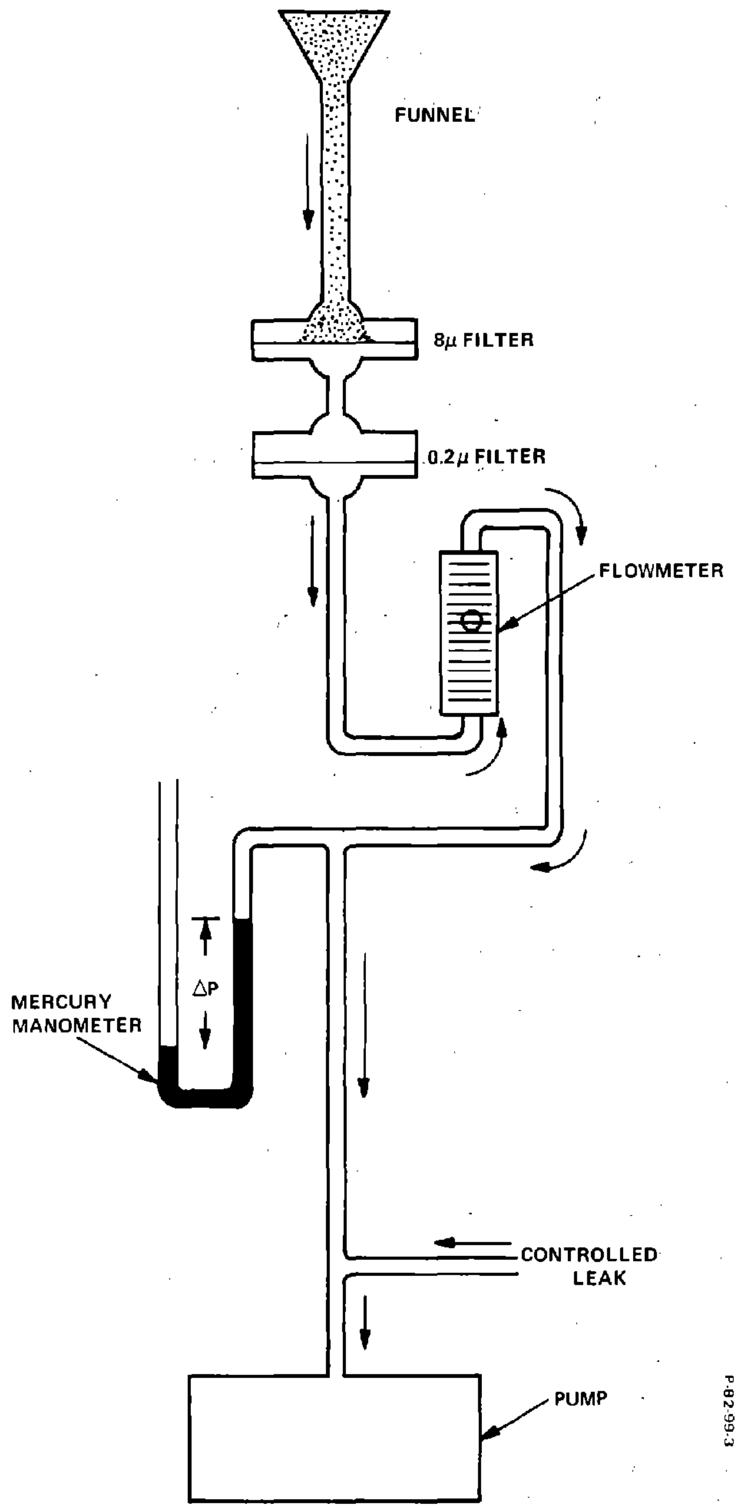


Figure B-1 - Sketch of Experimental Setup for Defining Filter Flow Characteristics of Nuclepore Membranes

Table B-1 - Flow Versus Pressure Drop Data

Unloaded Filters				Loaded Filter	
Run 1		Run 2		Run 1	
Flow (CFM)	ΔP (cm Hg)	Flow (CFM)	ΔP (cm Hg)	Flow (CFM)	ΔP (cm Hg)
0.9	1.0	0.9	1.0	0.9	1.0
2.3	3.4	2.3	3.7	2.0	3.1
3.8	6.2	3.8	6.5	3.0	4.1
5.9	11.0	7.7	17.1	4.0	7.2
7.7	16.6	9.7	24.2	5.0	9.6
9.7	23.9			7.0	15.2
11.0	28.9			9.0	22.7
12.0	33.4			11.0	30.6
				12.0	35.6

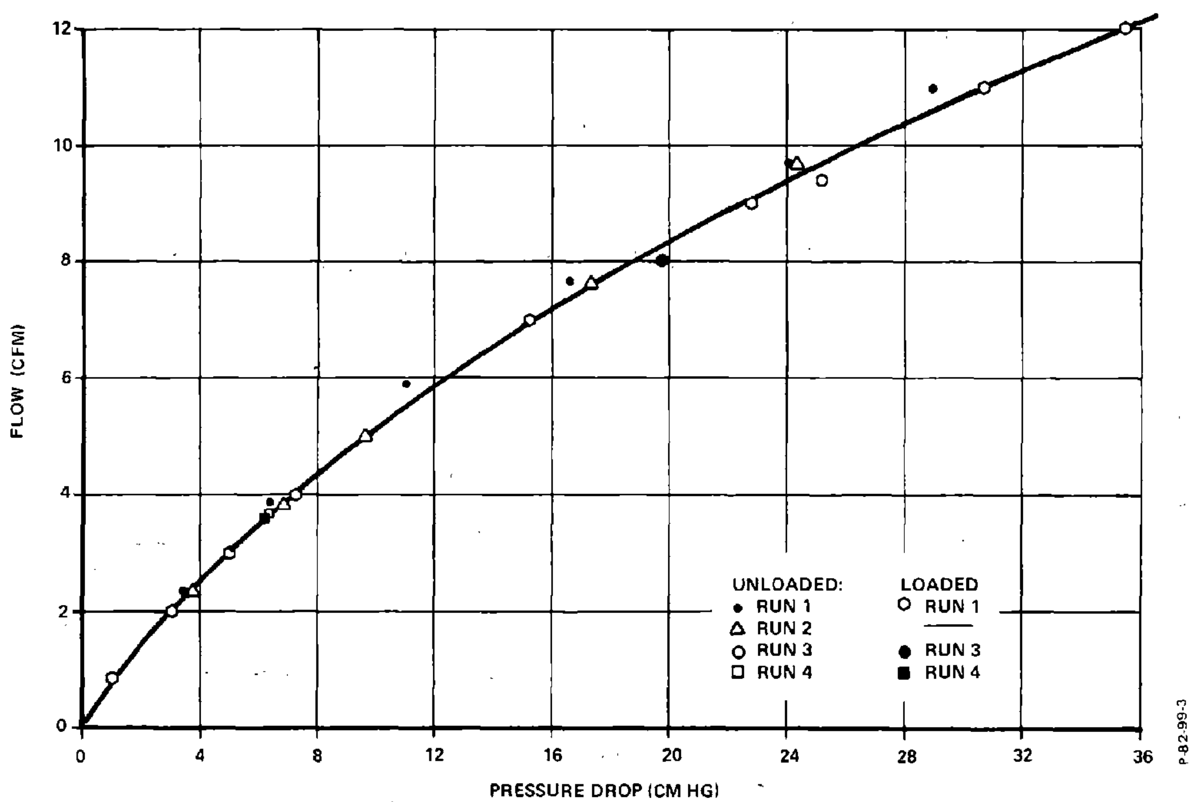


Figure B-2 - Plot of Flow Versus Pressure Drop

Table B-2 - Flow and Pressure Drop Versus Loading Data

Wear Debris Reservoir Weight (gm)	ΔW (mg)	Filter Loading (mg)	Pressure Drop (cm Hg)	Flow (CFM)
13.0160	—	0.0	52.7 - 27.6 = 25.1	9.4
13.0025	13.5	13.5	51.4 - 28.8 = 22.6	9.0
12.9744	28.1	41.6	51.3 - 28.9 = 22.4	9.0
12.9528	21.6	63.2	51.1 - 29.2 = 21.9	8.8
12.8883	64.5	127.7	50.7 - 29.6 = 21.1	8.7
12.7911	97.2	224.9	50.4 - 29.9 = 20.5	8.4
12.5590	232.1	457.0	50.3 - 30.0 = 20.3	8.3
12.3547	204.3	661.3	50.1 - 30.2 = 19.9	8.2
11.9800	374.7	1,036.0	50.0 - 30.3 = 19.7	8.0

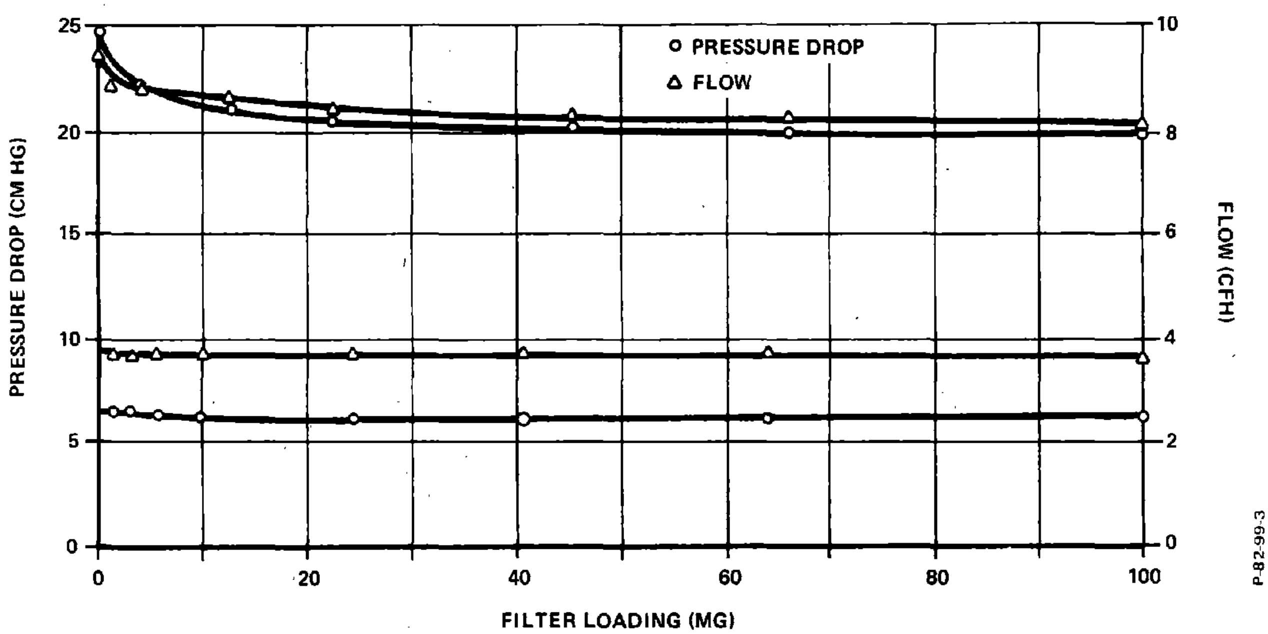


Figure B-3 - Plot of Pressure Drop and Flow Versus Filter Loading

Table B-3 - Flow and Pressure Drop Versus Loading Data

Wear Debris Reservoir Weight (gm)	ΔW (mg)	Filter Loading (mg)	Pressure Drop (cm Hg)	Flow (CFM)
13.7892	—	0.0	43.3 - 36.9 = 6.4	3.8
13.7741	15.1	15.1	43.3 - 36.9 - 6.4	3.7
13.7590	15.1	30.2	43.2 - 36.9 = 6.3	3.7
13.7416	17.4	47.6	43.2 - 36.9 = 6.3	3.7
13.7012	40.4	98.0	43.2 - 36.9 - 6.3	3.7
13.5552	146.0	234.0	43.2 - 36.9 - 6.3	3.7
13.3928	162.4	396.4	43.2 - 37.0 = 6.2	3.7
13.5198	233.0	629.4	43.2 - 37.0 = 6.2	3.7
12.8014	358.4	987.8	43.2 - 37.0 = 6.2	3.6

Additional Table B-3 Data:

- Removal of 8μ membrane from under debris after light shaking and air blow: 14.9 mg
  Original weight: 13.4
  Amount remaining on filter: 0.6 mg
- Weight of funnel plus tubing plus debris: 43,187.0 mg
  Weight of funnel plus tubing: 43,144.8
  Weight of debris trapped: 42.2 mg

B.5 CONCLUSIONS

- The flow rate through the filters is fairly reproducible for different membranes.
- Gas flow is proportional to pressure drop.
- Initial 1 to 2 mg/cm^2 loading reduces flow slightly (∿10 percent).
- Higher loading (up to 100 mg/cm^2) reduces flow an additional 10 percent.
- Wear debris can be separated from membrane and stored in a vial without any significant loss.

- Minimal losses will occur in the heated transfer line between the shroud and the filter holder.
- Over-all filter setup chosed for this project appears to operate satisfactorily for approximately 1 gram of collected debris. Larger amounts will require a pre-filter of several filter changes.

APPENDIX C

COLLECTION OF BRAKE AND CLUTCH EMISSIONS

Sequence	Description
1	Preparation of Collection Systems (Table C-1)
2	Installation of Collection System on Test Vehicle (Table C-2)
3	Preparation of Vehicle for Test (Table C-3)
4	Vehicle Test (Table C-4)
5A	Removal of Particulate Filters and Gas Collectors from Vehicle (Table C-5)
5B	Removal of Wear Debris from Disc Brake Emissions Collector (Table C-6)
5C	Removal of Wear Debris from Drum Brake Emissions Collector (Table C-7)
5D	Removal of Wear Debris from Clutch Emissions Collector (Table C-8)
6	Transfer of Samples to Analytical Laboratories (Table C-9)

Table C-1 - Preparation of Collection System for Vehicle Test - Sequence 1

Operation	Location	Responsibility	Remarks
Gas Collection System			
Rinse interior of condensable gas trap (only) with toluene (three rinses; $\sim$25 cc per rinse). Air dry. Assemble trap train. Check all connections.	Laboratory	Technician	Remove high molecular weight materials.
Heat trap train in vacuum oven at 100°C for one hour at vacuum (all valves open).	Laboratory	Technician	Remove residual gases from previous test.
Remove from oven and close valves.	Laboratory	Technician	
Clean, Label, and Weigh Vials	Laboratory	Technician	For wear debris: Sump sample; Surfaces sample; Additional
Particulate Filter Holders			
Remove O-ring, wipe clean with toluene. Air dry.			
Rinse filter holders with toluene until clean. Air dry.	Laboratory	Technician	Removes sludge.
Replace O-ring in holder.			
Weigh filter membranes.	Laboratory	Technician	From desiccator.
Reassemble particulate collection system.	Laboratory	Technician	

Table C-2 - Installation of Collection Systems - Sequence 2

Operation	Location	Responsibility	Remarks
Pick Up Gas Collection Systems (3), Particulate Filter Holders (3), and Vials with Laboratory Cart.	Laboratory/ Garage	Driver	Handle with care during transportation.
Cover with plastic sheet for transportation to garage.			
Install Gas Collection Systems (Three Systems)	Garage	Driver	Front Brake 1 or 2 Rear Brake 3 or 4 Clutch 5 or 6 (1, 3, 5 or 2, 4, 6 are on the same tests - do not change or mix.)
Connect ends			
Connect thermocouples			
Check temperatures			
Check inlet air drier and filters			
Install Particulate Filter Holders (Three Systems)	Garage	Driver	
Hoist vehicle			
Connect ends, pack insulation, tighten clamp			
Connect thermocouples			
Connect heater			
Check heating (50% power)			
Record temperatures			
Assemble Emissions Collectors	Garage	Driver	
Front			
Rear			
Clutch			

Table C-3 - Preparation of Vehicle for Test - Sequence 3

Operation	Location	Responsibility	Remarks
Prepare Record Sheets	Office	Driver/ Test Engineer	Review scheduled test.
Check Vehicle (Gas, Oil, Tires, Etc.)	Garage	Driver	
Fill Trap Boxes With Dry Ice	Garage	Driver	Handle with scoop or gloves.
Fill Dry Ice Storage Box (in Vehicle Trunk)	Garage	Driver	
Check Trap Temperatures	Garage	Driver	Must be colder than -70°C (-94°F).
Front			
Rear			
Clutch			
Check Battery and Inverter Electrical System	Garage	Driver	To ensure safe engine start.
Check Thermocouples, Brake Counter, Brake Gages, etc.	Garage	Driver	
Disconnect Battery Charger	Garage	Driver	
Start Engine, Restart Inverter, Record Odometer	Garage	Driver	
Adjust Air Flows	Garage	Driver	To ensure proper collection efficiency.
Front			
Rear			
Clutch			

Table C-4 - Vehicle Test - Sequence 4

Operation	Location	Responsibility	Remarks
Check Vehicle Test Record Sheets	Vehicle	Driver/ Test Engineer	Prepared prior to test.
Drive to Test Area	Vehicle		
Record Time, Mileage, Reset Brake Counter	Vehicle		
Record All Temperatures and Air Flows	Vehicle		
Perform Test	Vehicle	Driver/ Test Engineer	Periodically
Monitor Brake Temperature Balances (R to L)	Vehicle	Driver	Periodically
Record Maximum and Minimum Temperatures	Vehicle	Driver	Periodically
Monitor Emissions	Vehicle	Driver	Periodically
Collectors:			
Check flows Check temperatures			
Cold Boxes Particulate heaters			
Return Vehicle to Garage With Brake Temperatures Below 200°F.	Vehicle	Driver	

Table C-5 - Removal of Particulate Filters and Gas Collection from Vehicle - Sequence 5A

Operation	Location	Responsibility	Remarks
Park Vehicle in Garage Over Hoist	Garage	Driver	Immediately after completion of test.
Stop Engine	Garage	Driver	Immediately after completion of test.
Record Odometer and Brake Counter	Garage	Driver	Immediately after completion of test.
Close All Valves in Gaseous Collection System	Garage	Driver	Immediately after completion of test.
Turn Off Heaters	Garage	Driver	Immediately after completion of test.
Close Garage Door	Garage	Driver	Immediately after completion of test.
Check Gaseous Collection System and Top Up Dry Ice	Garage	Driver	Immediately after completion of test.
Remove Gaseous Collection Systems and Place on Cart (Clean)	Garage	Driver	Check and ensure valves are closed. Label location and run number.
Hoist Vehicle	Garage	Driver	
Remove Particulate Collection Systems and Place on Cart (Onto Shock-Proof Pad).	Garage	Driver	Handle with care. Do not bump.

Table C-6 - Removal of Wear Debris from Disc Brake Emissions Collector - Sequence 5B

Operation	Location	Responsibility	Remarks
Adjust Vehicle on Hoist	Garage	Driver	Wheels should be 1 to 2 inches above floor.
Remove Wheel. Visually Inspect Collector and Rotating Seal.	Garage	Driver	Record observation.
Clean Exterior Surfaces.	Garage	Driver	
Spread 4 x 5 foot Clean Plastic Sheet Below Wheel Well.	Garage	Driver	To protect clean smaller sheet to catch debris.
Spread 12" x 18" Clean Plastic Sheet Under Collector Shroud. Place Clean Vial Onto Sheet.	Garage	Driver	To catch wear debris. Vial previously cleaned and weighed.
Carefully Remove Rubbing seal and inspect Screws Outboard shield	Garage	Driver	Record inspection.
Vacuum Debris From Outboard Shield, Rotor, and All Other Brake and Collector Surfaces onto 0.2μ Nuclepore filter. Remove Caliper Cover Plate and Vacuum. Transfer Filter to Vial.	Garage	Technician	Label: Location Surfaces Sample Vehicle Test No. Schedule

(1 of 2)

Table C-6 - Removal of Wear Debris from Disc Brake Emissions Collector - Sequence 5B

Operation	Location	Responsibility	Remarks
Replace Plastic Sheet Under Open Collector.	Garage	Technician	
Remove Both Caliper Bolts and Remove Caliper. Vacuum the Pad Debris Onto 0.2μ Nuclepore Filter. Vacuum Wear Debris From Rivet Holes and From Inside of Caliper Piston.	Garage	Technician	Label: Location Sump Sample Vehicle Test No. Schedule
Remove Pads From Shoes.	Laboratory	Technician	
Dry, Weigh and Mike the Pads	Laboratory	Driver	Weigh to nearest 0.01 gm. Use SAE micrometer procedure.
Reassemble Brake and Collector.	Garage	Driver	

(2 of 2)

Table C-7 - Removal of Wear Debris From Drum Brake Emissions Collector - Sequence 5C

Operation	Location	Responsibility	Remarks
Remove Wheel. Visually Inspect Rotating Seal.	Garage	Driver	Record observations.
Clean Exterior Surfaces.	Garage	Driver	
Spread 4' x 5' Clean Plastic Sheet Below Wheel Well.	Garage	Driver	
Spread 12" x 18" Clean Plastic Sheet Under Collector (Shroud).	Garage	Driver	
Carefully Remove Drum and Set Down With Opening Facing Up.	Garage	Driver	
Collect Sump Sample Including Debris From Brake Shoe Rivet Holes and Place Into Vial.	Garage	Technician	Label: Location Sump Sample Vehicle Test No. Schedule
Vacuum Brake Surfaces and Drum Interior Onto 0.2μ Nuclepore Filter. Collect Wear Debris on First Plastic Sheet and Put Into Vial. Dismantle Brake and Vacuum all Parts. Vacuum Backing Plate. Transfer Filter.	Garage	Technician	Label: Location Surfaces Sample Vehicle Test No. Schedule

(1 of 2)

Table C-7 - Removal of Wear Debris From Drum Brake Emissions Collector - Sequence 5C

Operation	Location	Responsibility	Remarks
Remove Linings From Shoes.			
Dry, Weigh, and Mike Linings.	Garage	Driver	Record weights.
Reassemble Brake.	Garage	Driver	Wipe away any hydraulic oil.
Return 80% of Sump Wear Debris to Drum Surface.	Garage	Driver	Need for drum grinding action.
Replace Drum Assuring that no Debris Falls Out.	Garage	Driver	
Reassemble Collector (Shroud) Components	Garage	Driver	

(2 of 2)

Table C-8 - Removal of Wear Debris From Clutch Emissions Collector - Sequence 5D

Operation	Location	Responsibility	Remarks
Adjust Vehicle Height.	Garage	Driver	
Carefully Clean Exterior Surfaces	Garage	Driver	
Spread 4' x 5' Clean Plastic Sheet Below the Clutch.	Garage	Driver	
Spread 12" x 18" Clean Plastic Sheet Under Clutch	Garage	Driver	
Remove Clutch Cover.	Garage	Driver	
Vacuum Debris Onto 0.2μ Nuclepore Filter. Transfer to Vial.	Garage	Driver	Label: Location Sump Sample Vehicle Test No. Schedule.
Carefully Vacuum. All Other Surfaces Wear Debris.	Garage	Driver	Caution: oil mist on surfaces. Label: Location Surfaces Sample Vehicle Test No. Schedule
Weigh and Mike the Clutch Facing Assembly (at Start of First Vehicle Test and at Finish of Last Vehicle Test).	Garage	Driver	Record weight.
Reassemble Clutch and Collector (at Start of First Vehicle Test and at Finish of Last Vehicle Test).	Garage	Driver	

Table C-9 - Transfer of Samples to Analytical Laboratories - Sequence 6

Operation	Location	Responsibility	Remarks
Ensure All Samples are on Cart and Protected From Possible Shaking in Transfer to Labs	Garage	Technician	
Cover Cart With Plastic Sheet	Garage	Technician	
Transfer Cart and Samples to Analytical Lab	Laboratory	Technician	
Check-In All Samples and Verify Identification	Laboratory	Technician	Report to project engineer

APPENDIX D

ANALYSIS OF BRAKE AND CLUTCH EMISSIONS

Sequence	
7A	Process Particulate Filters (for Material Balance Considerations) (Table D-1)
7B	Redistribution of Particulates for Microscopy (Table D-2)
8A	Particulate Analysis by Optical Microscopy (Table D-3)
8B	Particulate Analysis by Electron Microscopy (Table D-4)
9	Asbestos Emissions and Size Distribution (Table D-5)
10A	Noncondensable Gaseous Emissions Processing (Table D-6)
10B	Analysis of Noncondensable Gaseous Emissions (Table D-7)
11A	Condensable Gaseous Emission Processing (Table D-8)
11B	Analysis of Condensable Gaseous Emissions (Table D-9)
12	Total Gaseous Emissions (Table D-10)

Table D-1 - Processing Particulate Samples - Sequence 7A

Operation	Location	Responsibility	Remarks
Airborne Samples			
Remove Filter Membrane From Filter Holders Over Clean 12" x 12" Plastic Place Filter Membranes Into Clean Vial. Brush Loose Debris Into Vial.	Laboratory	Technician	Use extreme care. Work in draft-free, ultra-clean area.
Accumulate Filter Membranes Pertinent to Same Test.	Laboratory	Technician	Some vehicle tests may have two or more filter sets (i.e., Detroit Traffic Test).
All Samples			
Desiccate All Filter Membranes and Vials of Particulates.	Laboratory	Technician	
Weigh All Samples	Laboratory	Technician	Record on test sheet.
Select Samples for Division for Battelle. Divide samples, Pack, and Ship.	Laboratory	Project Engineer Technician	Record selections. Use extreme care.
Low Temperature Ashing (LTA)			
Randomly Select 20 to 50 mg of Wear Debris From Vial and Distribute in Thin Layer Over LTA Boat.	Laboratory	Technician	Record weight and time.
Insert Into LTA. Initiate Plasma.	Laboratory	Technician	
Remove After 7 Hours and Redistribute Wear Debris in Boat.	Laboratory	Technician	Expose new surfaces to plasma.
Insert Into LTA. Initiate Plasma and Remove After Further 17 Hours.	Laboratory	Technician	
Redistribute Wear Debris and Insert Into LTA for additional 24 Hours.	Laboratory	Technician	Record weight loss after 48 hours elapsed LTA time.

Table D-2 - Redistribution of Particulates for Microscopy - Sequence 7B

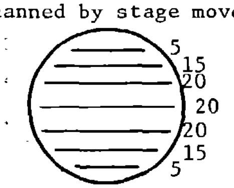
Operation	Location	Responsibility	Remarks
For each LTA Sample Weigh 0.55 $\pm$ 0.05 mg Onto Tiny Platinum Boat by Taking Several $\sim$0.05 mg Fractions from LTA Sample.	Laboratory	Technician	Preserve sample distribution.
Suspend in 100 cc of 1:1 Methanol:MEK in 250 cc Beaker	Laboratory	Technician	Use pre-filtered solvent. Use very clean beaker (rinsed with solvent).
Filter Onto 47 mm O.D. 0.2μ Nuclepore Membrane:			
Swirl Solution and Rapidly Pour Into Funnel.	Laboratory	Technician	Preserve random distribution.
Start Vacuum and Then Stop Solution Level About 1/2 cm above Filter.	Laboratory	Technician	Do not allow to dry. Use 3-way stopcock to control vacuum.
Wash Down Beaker and Add to Funnel	Laboratory	Technician	
Start Vacuum and Again Stop Level 1/2 cm above Filter.	Laboratory	Technician	Do not allow to dry. Use 3-way stopcock to control vacuum
Wash Down Funnel Sides with Solvent. Allow Last Wash to Filter to Completion.	Laboratory	Technician	
Cover Top of Funnel with a Clean Petri Dish Top and Pull Vacuum for 5 Minutes.	Laboratory	Technician	Cover keeps dirt out. Can also be used in above steps between washings.
Remove Filter and Store in Petri Dish.	Laboratory	Technician	Insure sample is labeled properly.

Table D-3 - Particulate Analysis by Optical Microscopy - Sequence 8A

Operation	Location	Responsibility	Remarks
Sample Preparation			
Insure Dust and Draft-Free Ambient Conditions.	Metallurgical Lab.	Microscopist	
Label a Clean Slide With a Frosted End for Easy Sample Identification. Rinse With Filtered Acetone.	Metallurgical Lab.	Microscopist	
Place 1 Drop of Solution With Refractive Index 1.585 in Center of Slide and Smear Into a Shape Corresponding to a Typical Filter Section.	Metallurgical Lab.	Microscopist	
Cut a Circular Section From Nuclepore Filter. Handl With Forceps. Place Nuclepore Filter on Top of Solution on Glass Slide.	Metallurgical Lab.	Microscopist	To reduce static charge of filters, use either of the following: α-emitter such as those sold by photographic houses to clean camera lenses. Ether-soaked swabs passed in air over the filter so that vapor will dissipate charge. Remove all bubbles.
Cover with Corning No. 1 Cover Slip (24 x 40 mm) to Flatten the Filter Paper and Hold the Mounting Medium in Place.	Metallurgical Lab.	Microscopist	
Store Sample in a Petri Dish or Slide Box Until Counting Takes Place.	Metallurgical Lab.	Microscopist	

(1 of 2)

Table D-3 - Particulate Analysis by Optical Microscopy - Sequence 8A

Operation	Location	Responsibility	Remarks
Counting Procedure			
Fill Out Count Sheet (Exhibit D-I).	Laboratory	Project Engineer	
Set Up Microscope With Heine Phase-Contrast Optics at 400X.	Metallurgical Lab.	Microscopist	
Calibrate the Microscope by the Following Procedure. The Length of the Large Reticle is 200 L Units. By Measuring the Actual Length of the Rectangle Using the Stage Micrometer and Dividing This Value by 200, the Value of L at the Magnification is Obtained.	Metallurgical Lab.	Microscopist	With this value for L, the actual diameter for each circle and the length of each individual area can be obtained for fiber sizing.
Place a Sample Slide on the Stage and Focus on the Top Surface of Filter. The Total Fiber Count Should be at Least 100 Fibers or 100 Fields, Whichever is Less.	Metallurgical Lab.	Microscopist	This sketch shows the distribution of 100 fields over several areas easily scanned by stage movement. 
Count All Fibers Crossing the Limits of the Counting Field on Two Adjacent Sides (Top and Left).	Metallurgical Lab.	Microscopist	During the count of each field, it is important to constantly adjust the fine focus back and forth. This brings into focus the fibers that might not be seen otherwise.
Record the Counts Into the Various Size Ranges Given on the Count Sheet.			

(2 of 2)

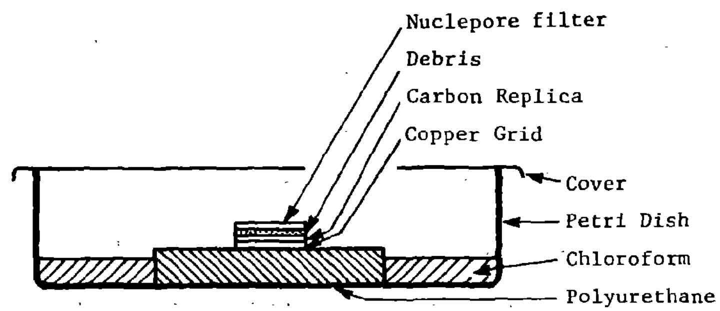
Table D-4 - Particulate Analysis by Electron Microscopy - Sequence 8B

Operation	Location	Responsibility	Remarks
Sample Preparation			
Cut Out a 1/2 inch Filter Circle of Nuclepore Filter With a Special Cutter and Mount on a Glass Microscope Slide With Scotch Tape.	Metallurgical Lab.	Technician	Use thin strip (1/4 inch wide) tape to hold filter.
Coat the Piece of Filter with Carbon in a Vacuum Coater.	Metallurgical Lab.	Technician	Pieces from 4 samples mounted on one slide and a total of 12 pieces on 3 different slides can be coated in one operation. Ladd Industries carbon appears to be best A 1 x 4 mm rod is used.
Use a Drop of Diffusion Pump Oil on Porecelain Plate to Determine Carbon Film Thickness.	Metallurgical Lab.	Technician	Color development should be dark yellow to yellow-brown.
Prepare Copper Grids (400 Mesh).	Metallurgical Lab.	Technician	
For Each Filter Sample, Place 2 to 3 Grids Onto a 3/8 Inch High Polyurethane Foam Block Sitting in Chloroform in a Petri Dish. The Surface of the Chloroform is About 1/8 Inch From the Top of the Polyurethane Block.	Metallurgical Lab.	Technician	
Cut a 1/8 Inch Diameter Disc (the Size of the Specimen Grid) From the Carbon-Coated Filter With a Sharp Specially-Made Boring Tool.	Metallurgical Lab.	Technician	The tool is machined from tool steel and hardened to the level of surgical steel.
With a Pair of Tweezers, Place the Carbon-Coated Filter Disc With Carbon Side Down Onto the Grid.	Metallurgical Lab.	Technician	This is a tricky operation: must place one edge down first and then rapidly lay down the other.

(1 of 3)

Table D-4 - Particulate Analysis by Electron Microscopy - Sequence 8B

Operation	Location	Responsibility	Remarks
Sample Preparation (Continued)			
Cover the Petri dish and Allow to Stand Approximately 3 Hours. Note: See Reference diagram below	Metallurgical Lab.	Technician	The Nuclepore filter is apparently dissolved by the the chloroform by wick action through the pores of the carbon replica.
Remove Grid with Carbon Film From Bath and Carbon Coat the Debris Side in the Vacuum Evaporator.	Metallurgical Lab.	Technician	
Store on a Filter Paper in Another Petri Dish. They are now Ready for Electron Microscopy.	Metallurgical Lab.	Technician	



(2 of 3)

Table D-4 - Particulate Analysis by Electron Microscopy - Sequence 8B

Operation	Location	Responsibility	Remarks
Sample Counting			
Fill Out Count Sheet	D-212	Project Engineer	
Calibrate the Microscope.	Metallurgical Lab.	Microscopist	Binocular magnification at 10X can be used for greater magnification.
Place a Sample Grid in the Microscope and Check Several Grid Openings to Ensure that the Grid is Suitable for Counting.	Metallurgical Lab.	Microscopist	
Set up EM at 22,000X for Fiber Identification by Morphology and Electron Diffraction.	Metallurgical Lab.	Microscopist	
Count and Record Fibers for Each of 20 Fields in a 400 Mesh Specimen Grid. Use a Hand Counter or Other Method to Record the Number of Fields Counted.	Metallurgical Lab.	Microscopist	A field is defined as an area within the square etched on the grid.
Count all Fibers Crossing the Limits of the Counting Field on Two Adjacent Sides (Top and Left). Record the Counts in the Various size Ranges Given on the Count Sheet (Exhibit D-I).	Metallurgical Lab.	Microscopist	
Electron and/or X-ray Diffraction			
Check Crystallinity of Several Particles and Fibers, and/or Fields.	Metallurgical Lab.	Microscopist	Record typical diffraction patterns.

(3 of 3)

Table D-5 - Asbestos Emissions and Size Distribution - Sequence 9

Operation	Location	Responsibility	Remarks
Total the Number of Fibers in Each Size Category	D-212	Project Engineer	
Calculate the Total Fiber Volume	D-212	Project Engineer	
Calculate the Total Fiber Weight.	D-212	Project Engineer	
Calculate the Total Fiber Concentration	D-212	Project Engineer	
Calculate and Plot the Asbestos Particle Size Distribution	D-212	Computer	

Table D-6 - Noncondensable Gaseous Emissions Processing - Sequence 10A

Operation	Location	Responsibility	Remarks
Fill Out Gas Analysis Sheet (Exhibit D-II).	D-212	Project Engineer	
Check Gas Storage Box.	Analytical Lab.	Gas Chromatographer	Record condition.
Start Up Gas Chromatograph With Porapak Column Installed.	Analytical Lab.	Gas Chromatographer	See conditions in Exhibit D-III.
Start Up Gas Processing Equipment	Analytical Lab.	Gas Chromatographer	
Connect Noncondensable Gas Trap to Gas Inlet Tap With Vacuum Tubing. Pump Out Tubing.	Analytical Lab.	Gas Chromatographer	Insure good seal prior to further processing.
Place Dry Ice Trap Around Primary Inlet Trap. Place Liquid Nitrogen Around Secondary Inlet Trap.	Analytical Lab.	Gas Chromatographer	To remove any possible condensable.
Maintain Gas Storage Box at Dry Ice Temperature. Open Taps and Allow Nonabsorbed Gases to Escape From All 3 Traps.	Analytical Lab.	Gas Chromatographer	To remove carrier air from sample. Check vacuum return periodically.
Isolate Condensable Gas Trap.	Analytical Lab.	Gas Chromatographer	To be analyzed later separately.
Pump Out G.C. Sample U-Tube. Close High Vacuum Tap to Isolate Manifold. Remove LN_2 Trap.	Analytical Lab.	Gas Chromatographer	Top-up DI trap.
Remove DI in Gas Storage Box and Raise to Ambient.	Analytical Lab.	Gas Chromatographer	
Begin Collection of Adsorbed Noncondensable Gases in Gas Burette With Toepler Pump.	Analytical Lab.	Gas Chromatographer	If amount appears to be large, close valves and isolate a portion.
Complete Gas Measurement. Select a Portion for Analysis by G.C. Discard Remainder or Store a Portion in an Empty Gas Storage Volume.	Analytical Lab.	Gas Chromatographer	Record quantities and G.C. results Exhibit D-III for each fraction.
Collect Additional Fractions Until All Gases are Measured and Analyzed.	Analytical Lab.	Gas Chromatographer	Record as above.

Table D-7 - Analysis of Noncondensable Gaseous Emissions - Sequence 10B

Operation	Location	Responsibility	Remarks
Insure G.C. Parameters are Properly Set for Porapak Column.	Analytical Lab.	Gas Chromatographer	See Exhibit D-III
Check Base-Line Stability of Thermal Conductivity Detector.	Analytical Lab.	Gas Chromatographer	Attenuation X1.
Select a Portion of Gas Burette Sample for G.C. Analysis.	Analytical Lab.	Gas Chromatographer	Use 4.98 cc volume at 5 to 15 cm pressure.
Open Gas Burette 3-Way Tap and Push Gas Sample Into Sample U-Tube. Raise Mercury to Tap of Gas Burette.	Analytical Lab.	Gas Chromatographer	Do not allow mercury into bore of top.
Close 3-Way Tap.	Analytical Lab.	Gas Chromatographer	
Turn G.C. Recorder On. Adjust Chart Paper to Record Injection Time. Record Sample Identification on Chart.	Analytical Lab.	Gas Chromatographer	
Inject Sample. Record Injection Time and Attenuation.	Analytical Lab.	Gas Chromatographer	After 10 sec., return top to normal He flow positions.
Monitor G.C. Analysis.	Analytical Lab.	Gas Chromatographer	
Lower Mercury Level in Gas Burette. Keep Mercury Seat Valve Open.	Analytical Lab.	Gas Chromatographer	Use magnet to hold open.
Open High Vacuum Tap to Diffusion Pump.	Analytical Lab.	Gas Chromatographer	
Open 3-Way Tap to Pump Out G.C. Sample U-Tube.	Analytical Lab.	Gas Chromatographer	
Monitor G.C. Retention Times, Peak Heights and Attenuation Settings.	Analytical Lab.	Gas Chromatographer	Caution: Monitor pen to insure full record.
Check Gas Burette Vacuum. Close 3-Way Tap to Isolate G.C. Sample U-Tube. Prepare a Calibration Sample for G.C. From a Gas Storage Bulb.	Analytical Lab.	Gas Chromatographer	
Inject Calibration Sample and Record as Above.	Analytical Lab.	Gas Chromatographer	
(Run Infrared Analysis).	Analytical Lab.	Gas Chromatographer	(Inject sample into gas cell through sample U-tube.)

Table D-8 - Condensable Gaseous Emissions Processing - Sequence 11A

Operation	Location	Responsibility	Remarks
Insure Condensable Gas Trap is Under Vacuum.	Analytical Lab.	Gas Chromatographer	
Place Dry-Ice Around First Distillation Trap and LN_2 Around Second Trap.	Analytical Lab.	Gas Chromatographer	
Distill Contents of Condensable Gas Trap Through Traps in Gas Handling System.	Analytical Lab.	Gas Chromatographer	
After Distillation, Allow LN_2 Trap to Ambient Temperature and Determine Amount and Composition of Noncondensable Gases.	Analytical Lab.	Gas Chromatographer	
Replace Tubing at Gas Inlet With a Specially Built, Weighed Glass Vessel.	Analytical Lab.	Gas Chromatographer	Clean vessel with solvent and regrease stop-cock.
Evacuate and Isolate the First Trap and This Vessel. Heat Trap and Cool Vessel so that a Vacuum Distillation Transfers Condensable Gases to Vessel.	Analytical Lab.	Gas Chromatographer	
When All Liquid is Transferred, Close Stop-Cock and allow to come to Ambient	Analytical Lab.	Gas Chromatographer	
Weigh and Determine Weight of Condensable Gases.	Analytical Lab.	Gas Chromatographer	
Analyze by Gas Chromatography.	Analytical Lab.	Gas Chromatographer	

Table D-9 - Analysis of Condensable Gaseous Emissions - Sequence 11B

Operation	Location	Responsibility	Remarks
Insure G.C. Parameters are Properly Set for Silicone Gum Column.	Analytical Lab.	Gas Chromatographer	See Exhibit D-III
Check Base-Line Stability of Flame Ionization Detector.	Analytical Lab.	Gas Chromatographer	Attenuation X1 Range 10.
Turn G.C. Recorder On. Adjust Chart Paper to Record Injection Time. Record Sample Identification On Chart.	Analytical Lab.	Gas Chromatographer	
Inject 1.0 μl Sample. Record Injection Time and Attenuation.	Analytical Lab.	Gas Chromatographer	
Monitor G.C. Analysis.	Analytical Lab.	Gas Chromatographer	Monitor temperature programming.
Run Calibration Blend.	Analytical Lab.	Gas Chromatographer	Periodically.
(Run Infrared Analysis.)	Analytical Lab.	Gas Chromatographer	(Periodically. Blank out solvent plus calibration.)

Table D-10 - Total Gaseous Emissions - Sequence 12

Operation	Location	Responsibility	Remarks
Total the Number of Moles of Each Noncondensable Gas Produced.	Laboratory	Project Engineer	
Relate the Number of Moles of Condensable Gases Formed to the Internal Calibration and to the Calibration Blend.	Laboratory	Project Engineer	
Calculate the Carbon Content in Grams.	Laboratory	Project Engineer	
Total the Carbon Content.	Laboratory	Project Engineer	Can be related to weight lost x organic fraction x carbon fraction.

Exhibit D-I

MICROSCOPY COUNT SHEET

Vehicle Test: ______
Schedule: ______
Collector: ______
Sample: ______
Date: ______

Total Sample Weight: ___.___ mg
LTA Weights (I/F): ___.___/___.___ mg
Count Weight: ___.___ mg
Comments:

22,000X

	FIBER DIAMETER (µ)	1	2	3	4	5	6	7	8	
		FIBER LENGTH (µ)								
	MIN / MAX	0.05 / 0.25	0.25 / 0.50	0.50 / 1.5	1.5 / 5.0	5 / 10	10 / 20	20 / 30	30 / 50	>50
11	0.02 / 0.03							Date Counted: ______		
12	0.03 / 0.05							EM Field Size: 3.0 x 3.0µ		
13	0.05 / 0.08							No. of Fields: ______		
14	0.08 / 0.25									
15	0.25 / 0.50									
16	0.50 / 1.0									

400X

	FIBER DIAMETER (µ)									
		FIBER LENGTH (µ)								
	MIN / MAX		0.5 / 1.0	1.0 / 3.0	3.0 / 10.0	10 / 20	20 / 35	35 / 60	60 / 100	
25	0.50 / 1.0									
26	1.0 / 2.0									
27	2.0 / 3.0									
28	3.0 / 4.0									
29	4.0 / 5.0									
30	5.0 / 7.0									
31	7.0 / 10.0									
	>10									

Date Counted: ______
OM Field Size: 88 x 88µ
No. of Fields: ______

Microscopist: ______

Exhibit D-II - Gaseous Emissions Data

Sample: ________________ Sample Date: ________________

Run No: ________________ Analyst: ________________

Location: ________________ Analysis Date: ________________

Box No: ________________

Comments:

Noncondensable Emissions:

P =

V =

T =

n =

H_2

N_2

O_2

CO

CH_4

CO_2

C_2H_6

Condensable Emissions:

Sample Plus Tare:

Tare:

Sample:

Exhibit D-III

	ANALYSIS OF NONCONDENSABLE GASEOUS EMISSIONS	ANALYSIS OF CONDENSABLE GASEOUS EMISSIONS
INSTRUMENT SETTINGS:		
Column:	10' 1/8" O.D. Stainless Steel packed 80/100 mesh Porapak Q	6' 1/8" O.D. Stainless Steel packed with 10% W-98 on 80/100 mesh Chromosorb W
Flow:	40 cc/min He	40 cc/min He
Temperature Program:	-80°C to 160°C programmed at 10°C/min.	25°C to 260°C programmed at 6°C/min.
Detector Temperature:	160°C (Dual Thermal Conductivity)	300°C (Dual Flame Ionization)
ELUTION ORDER:	Hydrogen	C_3 to C_4's
	Nitrogen	Benzene
	Oxygen	Toluene
	Carbon Monoxide	Xylenes
	Methane	Phenols
	Carbon Dioxide	Cresols
	Ethane	DM and TM Phenols
	Water	n-C_{16} solvent
	C_3 to C_4's	n-C_{20} calibration

APPENDIX E

ELECTRON MICROSCOPY ANALYSIS OF BRAKE EMISSION SAMPLES

E.1 SUMMARY

The previously developed technique for preparing brake emission debris for viewing with the electron microscope was found to be unsatisfactory for test car samples. That procedure was developed with standards and employee vehicle wear debris. When applied to the test vehicle brake emissions, excessive film breakage and instability occurred. Consequently, the technique was modified so that it was reasonably sure that no further difficulties would be encountered with the remaining samples to be analyzed. Basically success was achieved with (1) use of a finer copper grid, (2) double carbon film, and (3) reduced debris loading on the film. The details of the procedure, as modified, are given in Exhibit E-1.

E.2 PROBLEM

The difficulty with the previously developed procedure was manifested by the following:

(1) Fracture of the carbon film occurred during the cleaning operation employed to remove the filter. The fracture was so severe that carbon film coverage of the copper grid varied from 0 to 10% of the area originally covered.

(2) The large wear debris particles were unstable under the electron beam (expansion and contraction). This particle movement tore the film and released the wear debris so that analysis was impossible.

(3) The filter and carbon film appeared to shrink under the action of the cleaning solvent. This raised the question as to whether concentration of the wear debris was occurring because of the shrinkage and in this way creating a discrepancy between the real and observed number of particles per unit area.

E.3 PROBABLE CAUSES

It was assumed that the first two difficulties were created by the large nonasbestos wear debris particles. These particles appeared larger than those previously found in wear debris samples from the employee vehicle drum surfaces. The large particles apparently cause film tears because they created thin spots or openings in the carbon film during evaporation attributable to shadowing effects. These weak spots in the film and the bulk of the particles then contributed to film tearing during the strains of the cleaning operation. The particle instability under the electron beam could be attributed to heating and charging effects. The third difficulty occurred because the filter shrank under the action of the solvent before dissolving. Since the carbon film and filter were initially attached, the filter stressed the carbon film and also caused it to distort or crack.

E.4 SOLUTION ATTEMPTED

The following procedures or materials were tried in an attempt to eliminate the film breakage problem.

(1) A range of film thicknesses was investigated from thinner to thicker than that previously used.

(2) Silicon monoxide films were used in the hope that they would provide additional strength.

(3) Different films and film combinations were tried. These included chromium, platinum-carbon, chromium on carbon and collodion on carbon.

(4) Extreme care was exercised in laying the film on the grid prior to cleaning in order to ensure no handling breakage.

(5) The time to clean the filter from the film was shortened in an attempt to prevent breakage during cleaning.

(6) The cleaning solution was diluted or saturated in an attempt to reduce the severity of the cleaning operation.

(7) Carbon film was cleaned both while on a rough and on a smooth side of carbon grid.

(8) Vacuum drying of the film following cleaning was tried to remove all traces of residual solvent in case this was the cause of particle instability under the beam.

(9) A finer mesh grid (400 instead of 200) was tried to provide greater support for the carbon film.

(10) A second carbon film was vaporized over the wear debris and onto the original film following the cleaning operation. This sandwiched the wear debris between two carbon films. It was hoped that the additional film would provide additional strength and reduce particle instability.

E.5 SUCCESSFUL APPROACHES

Only the last three of the above mentioned techniques proved significant in combating film breakage and instability: fine mesh grid, double carbon film and lower debris loading on the film. The 400 mesh grid apparently provided greater support for the film and did reduce breakage during cleaning. The second carbon film applied after cleaning measurably strengthened the original film. Although there still appeared to be some particle instability under the beam the double film was strong enough to resist tearing.

The effect of the degree of loading on film integrity following cleaning is shown in Figure E-1. The debris was an air-borne sample taken from the right rear brake following the baseline test. All samples were on a 400 mesh grid and received a double carbon film. The debris loadings on the submitted filters were 1, 0.50, and 0.30 mg. The last two show good film coverage while the 1 mg loading shows extensive breakage. Also the 1 mg loading showed more stability under the beam than did the other two. Therefore, even though the counting time was increased because of the decreased loading, the filter loading was reduced to less than 0.60 mg.

Another consideration in selecting the debris loading for the film was the possibility that the large particles would mask the asbestos fibers. Considering the extreme, if the debris were concentrated to the extent that particles covered the entire grid opening, few fibers would be seen. The debris distribution for several initial filter loadings is shown in Figure E-2.

The possibility of erroneous results due to film shrinkage with attendant concentration of the debris was investigated. It did not seem reasonable that debris concentration would occur because the debris was attached to the carbon film and the carbon film itself would not shrink under the action of the solvent. Since the periphery of the carbon film was changing it was assumed that this could only occur by fracture or distortion of the film. Optical microscopy confirmed the assumptions. The film did not undergo shrinkage, but rather accomplished the dimensional change by forming folds as shown in Figure E-3. These folds were confined mainly to the periphery and would not pose any difficulty to the measurement as long as the folded area was avoided. In other films the folds were not confined entirely to the periphery, however, these areas could easily be avoided during the counting as they were readily detectable on viewing with the electron microscope. Therefore, the film folding under the action of the solvent posed no serious difficulties in the analysis.

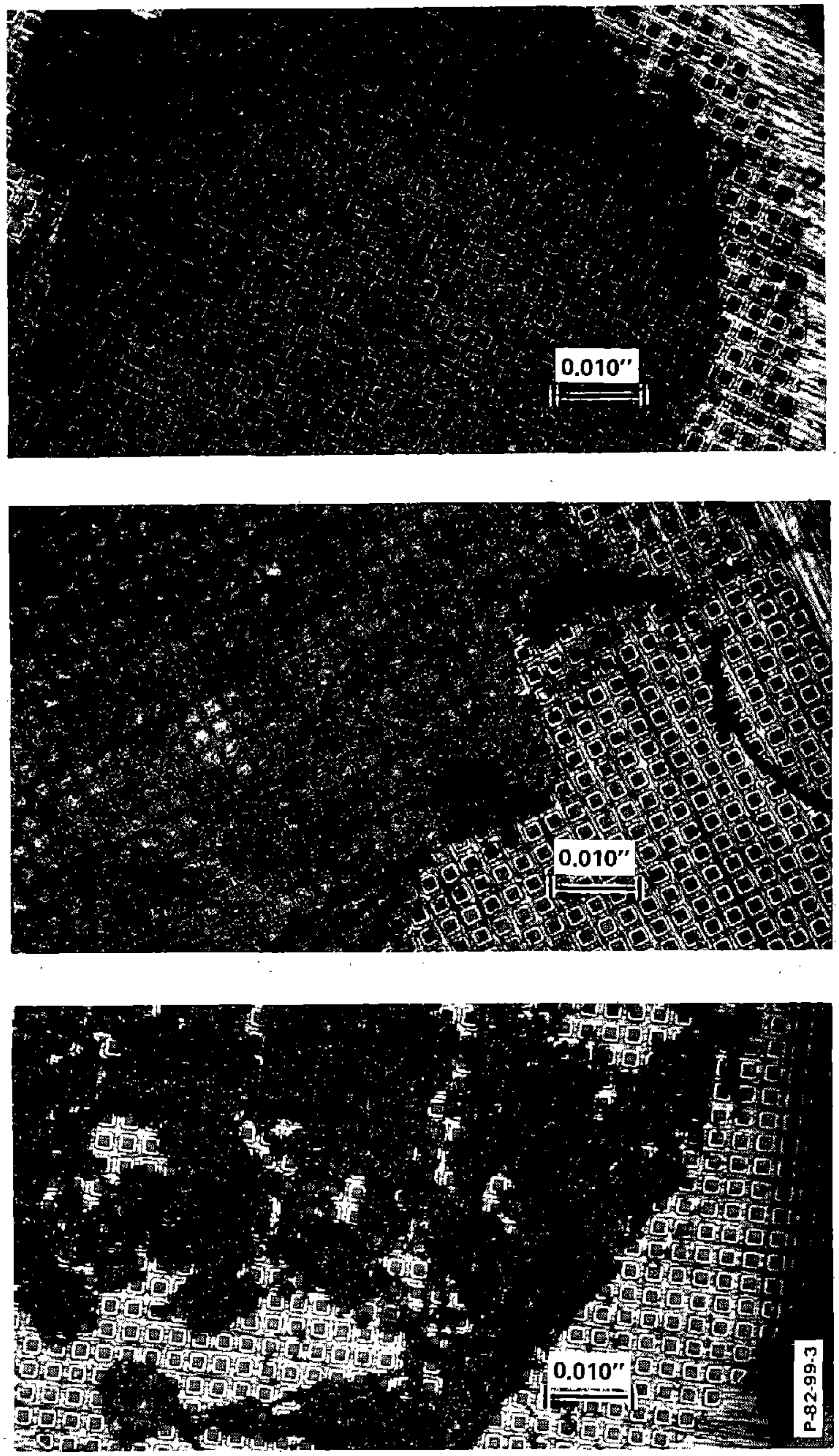


Figure E-1 - Photomicrographs of Carbon Films on 400-Mesh Grid 50X
[Films were made from filters with original debris loading of 0.3 (upper), 0.5 (center) and 1 (lower) mg. Debris was airborne collection from A.B. Baseline schedule of vehicle test for right rear drum brake]

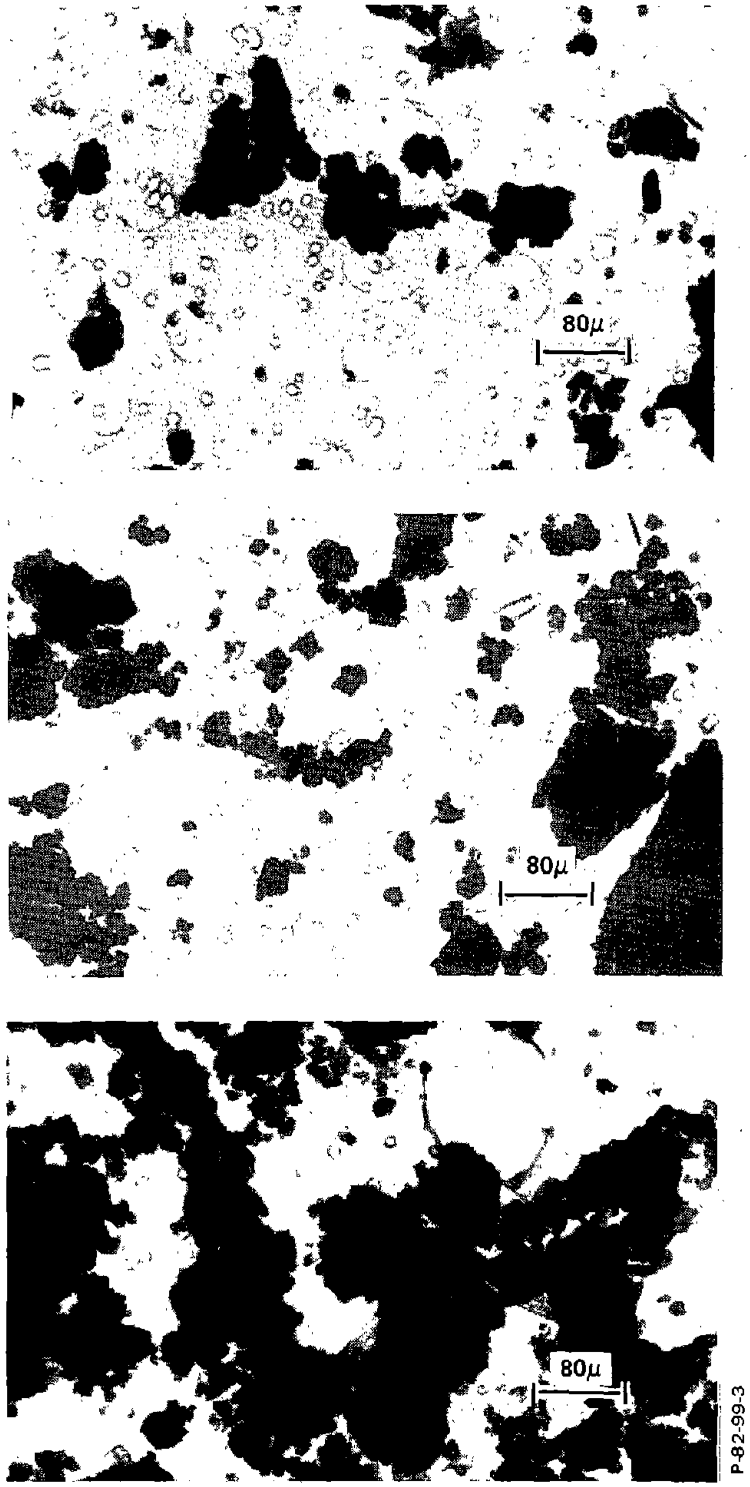


Figure E-2 - Electron Micrographs of Debris Distribution on Carbon Films Made from Initial Filter Loadings of 0.3 (upper), 0.5 (center) and 1 (lower) mg. (Debris was airborne collection from Baseline test) 6000X

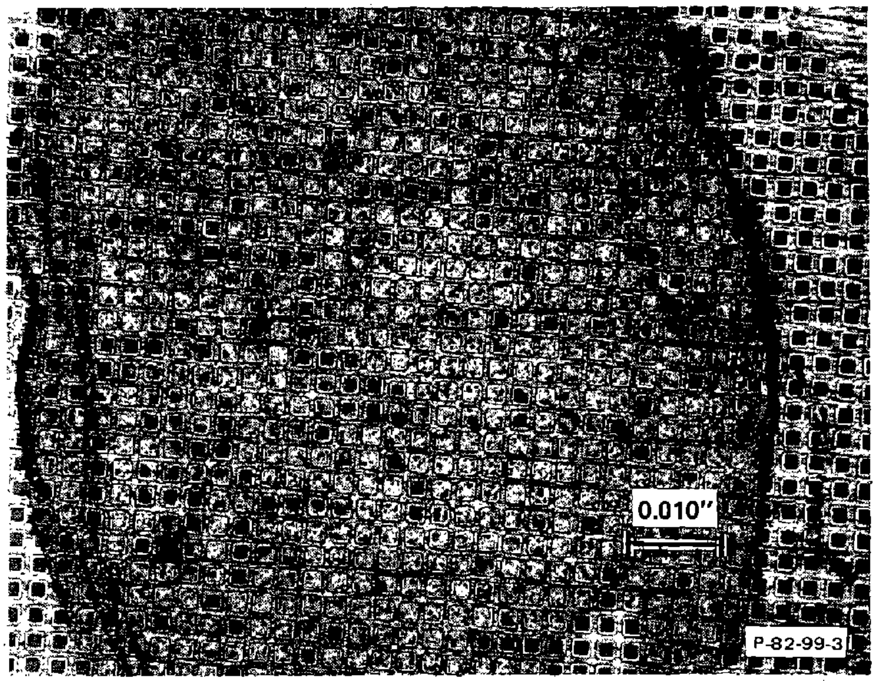


Figure E-3 - Photomicrograph of Carbon Film on 400-Mesh Grid Following Cleaning Operation. 50X (Shrinkage was due to film folds near periphery of film. Film was made from filter with 0.5 mg debris loading.)

E.6 CONCLUSIONS

1. The modified technique for preparing electron microscopy samples should provide a trouble-free method for analyzing all samples required for the program.
2. Loading of the filter was limited to less than 0.6 mg. This was required to prevent film breakage and, in addition, there was less chance of the large particles masking the asbestos fibers.
3. Film folding during cleaning did not introduce error into the analysis.

EXHIBIT E-I

PROCEDURE FOR ELECTRON MICROSCOPY ANALYSIS OF BRAKE EMISSION SAMPLES

1. Receive and log in sample.
2. Cut out 1/2-inch filter circle with special cutter.
3. Mount filter circle (debris side up) on glass slide with tape.
4. Vacuum evaporate carbon film on filter circle (4 mm length of carbon rod; 1 mm in diameter).
5. Remove from evaporator and cut out four 1/8-inch circles with special cutter.
6. Prepare cleaning bath to remove filter from carbon film by the following steps. Put polyurethane foam block in a petri dish and fill with chloroform to about 1/8-inch below the foam surface. Put 400 mesh copper grids on the top surface of the foam.
7. Place 1/8-inch carbon-coated circles on grids in the chloroform bath with carbon side down.
8. Let sample clean in bath at least 3 hours. Bath is covered during cleaning to prevent contamination.
9. Remove the carbon film on the grid from bath and carbon coat the debris side in the vacuum evaporator.
10. Remove from evaporator and view in transmission electron microscope.

APPENDIX F

COMPUTER PROGRAM FOR COMPUTATION OF ASBESTOS CONTENT USING ANALYTICAL MICROSCOPY TECHNIQUES


```
C***********************************************************************
C     IN TWO DIMENSIONAL ARRAYS, INDEX I CORRESPONDS TO ROWS 11 - 14,
C          15+25, 16+26, 27 -31 ON MICROSCOPY COUNT SHEET AND INDEX J
C          CORRESPONDS TO COLUMNS 1 - 8 ON MICROSCOPY COUNT SHEET.
C***********************************************************************
      DIMENSION BOX(49),VOL(12,8),IVOL(12,8),FCTR(2),VPLT(49)
     1 ,INM(8),XOL(12,8),
     1  IVH(5),ISCH(20),ICOL(20),ISAMP(20),IDATE(10),TOT(2)
C***********************************************************************
C     ARRAY XOL CONTAINS VOLUME * 10**12.
C***********************************************************************
      DATA XOL/.077E-3,.2E-3,.53E-3,9*0.0,
     2     .192E-3,.5E-3,1.31E-3,10.15E-3,8*0.0,
     3     .51E-3,1.34E-3,3.5E-3,27.1E-3,123.E-3,.982,6*0.0,
     4     1.66E-3,4.25E-3,11.3E-3,98.0E-3,401.E-3,3.19,12.8,33.2,63.6,
     4     3*0.0,
     5     3.83E-3,10.E-3,26.3E-3,203.E-3,890.E-3,7.3,29.4,76.7,147.,
     5     241.,436.,0.,
     6     7.77E-3,20.E-3,52.6E-3,406.E-3,1780.E-3,13.5,53.8,141.,270.,
     6     433.,805.,1.62E3,
     7     4*0.0,2960.E-3,23.3,93.,243.,466.,765.,1380.,2.89E3,
     8     4*0.0,4740.E-3,39.3,157.,409.,784.,1290.,2.33E3,4.69E3/
C***********************************************************************
C     FCTR(1) MULTIPLIES ROWS 11-16.  FCTR(2) MULTIPLIES ROWS 25-31.
C***********************************************************************
      DATA FCTR/110.E6,.12784E6/
      DO 190 I=1,12
      PRINT 999,I,(XOL(I,J),J=1,8)
  999 FORMAT(I5,8E14.5)
  190 CONTINUE
      STEP=1.0/6.0
C***********************************************************************
C     COMPUTE ARRAY BOX FOR LOG-LOG PLOT.  BOX = 10**-16 TO 10**-8 IN
C          STEPS OF 10**1/6.
C***********************************************************************
      DO 10 I=1,49
      BOX(I)=STEP*(I-1)-4.0-13.0
   10 CONTINUE
C***********************************************************************
C     COMPUTE VOL(I,J) = THE LOG OF XOL(I,J) AND MULTIPLY XOL (I,J) BY
C          10**-12
C***********************************************************************
      DO 20 I=1,12
      DO 20 J=1,8
      IVOL(I,J)=0
      VOL(I,J)=0.0
      IF(XOL(I,J).EQ.0.)GO TO 20
      VOL(I,J)=ALOG10(XOL(I,J))-12.0
      XOL(I,J)=XOL(I,J)*1.E-12
C***********************************************************************
C     COMPARE VOL(I,J) TO ARRAY BOX.  ASSIGN NUMBER OF CLOSEST BOX TO
C          IVOL(I,J).
C***********************************************************************
      DO 30 K=1,49
      IF(VOL(I,J).LE.BOX(K))GO TO 40
   30 CONTINUE
      K=49
   40 IVOL(I,J)=K
```

```
   20 CONTINUE
      DO 50 I=1,49
      BOX(I)=10.0**BOX(I)
   50 CONTINUE
      DO 191 I=1,12
      PRINT 999,I,(VOL(I,J),J=1,8)
  191 CONTINUE
C
C     START DOING STUFF
C
C***************************************************************************
C     READ HEADING CARD.
C***************************************************************************
  100 READ (5,900,END=500) ID1,(IVH(I),I=1,5),(ISCH(J),J=1,20),
     1  (ICOL(K),K=1,20),(ISAMP(L),L=1,20),(IDATE(M),M=1,10)
  900 FORMAT(I4,1X,75A1)
      READ (5,901) ID,TOTWT,XI,XF,XCNT
  901 FORMAT(I4,6X,4E10.0)
      IF(ID.NE.ID1)GO TO 501
      TOTWT=TOTWT*.001
      XI=XI*.001
      XF=XF*.001
      XCNT=XCNT*.001
      DO 200 I=1,49
      VPLT(I)=0.0
  200 CONTINUE
C***************************************************************************
C     TOT(1) = SUM OF ROWS 11-16.  TOT(2) = SUM OF ROWS 25-31.
C***************************************************************************
      TOT(1)=0.0
      TOT(2)=0.0
      TOTAL=0.0
  110 READ (5,920) ID,I,J,(INM(K),K=1,8),ITOT
      IF(ID.NE.ID1)GO TO 501
  920 FORMAT(I4,2I1,4X,8I3,6X,I5)
      IF(I.EQ.2)J=J+1
      IF(I.EQ.3)J=J+11
      IF(I.EQ.3)I=2
      DO 120 K=1,8
      TOT(I)=TOT(I)+2.56*XOL(J,K)*INM(K)*FCTR(I)/ITOT
      IF(IVOL(J,K).EQ.0)GO TO 120
      VPLT(IVOL(J,K))=VPLT(IVOL(J,K))+INM(K)*FCTR(I)/ITOT
  120 CONTINUE
C***************************************************************************
C     TEST FOR LAST DATA CARD.
C***************************************************************************
      IF(I.EQ.2.AND.J.EQ.12)GO TO 130
      GO TO 110
  130 CONTINUE
      TOTAL=TOT(1)+TOT(2)
      PCT=TOTAL*XF*100.0/(XCNT*XI)
      PRINT 911
  911 FORMAT('1',45X,'**** ASBESTOS ANALYTICAL RESULTS ****')
      PRINT 912,TOT(1),TOT(2)
  912 FORMAT('0',105X,'FM SUB TOTAL =',E11.4,/105X,'OM SUB TOTAL =',
     1  E11.4)
      PRINT 910,(IVH(I),I=1,5),(IDATE(J),J=1,10),XI,TOTAL,
     1  (ISCH(K),K=1,20),ID1,XF,XCNT,
```

```
                  1  (ICOL(L),L=1,20),
                  1   (ISAMP(M),M=1,20),PCT
 0067          910 FORMAT('OVEHICLE TEST: ',5A1,30X,'DATE: ',10A1,13X,'LTA(I)=',F11.4
                  1,16X,'TOTAL =',E11.4,/    5X,'SCHEDULE: ',20A1,15X,' NO.: ',I5,18X,
                  2'LTA(F)=',F11.4, 9X,'COUNT WEIGHT =',E11.4,/' ',3X,'COLLECTOR: ',
                  320A1,/' ',6X,'SAMPLE: ',20A1,50X,'ASBESTOS PERCENT =',F7.3,'%',/)
 0068              CALL LGPLT(BOX,VPLT,49)
 0069              GO TO 100
 0070          500 STOP 1
 0071          950 FORMAT('1 CARDS OUT OF ORDER ON RUN NO.',I5)
 0072          501 PRINT 950,ID1
 0073              STOP 999
 0074              END
```



```
                              SUBPROGRAMS CALLED
SYMBOL     LOCATION      SYMBOL     LOCATION      SYMBOL     LOCATION      SYMBOL     LOCATION      SYMBOL     LOCATION
IBCOM#        14C        FRXPR#        150        LGPLT         154        ALOG10        158

                              SCALAR MAP
SYMBOL     LOCATION      SYMBOL     LOCATION      SYMBOL     LOCATION      SYMBOL     LOCATION      SYMBOL     LOCATION
I             174        J             178        STEP          17C        K             180        ID1           184
L             188        M             18C        ID            190        TOTWT         194        XI            198
XF            19C        XCNT          1A0        TOTAL         1A4        ITOT          1A8        PCT           1AC

                              ARRAY MAP
SYMBOL     LOCATION      SYMBOL     LOCATION      SYMBOL     LOCATION      SYMBOL     LOCATION      SYMBOL     LOCATION
BOX           180        VOL           274        IVOL          3F4        FCTR          574        VPLT          57C
INM           640        XOL           660        IVH           7E0        ISCH          7F4        ICOL          844
ISAMP         894        IDATE         8E4        TOT           90C

                              FORMAT STATEMENT MAP
SYMBOL     LOCATION      SYMBOL     LOCATION      SYMBOL     LOCATION      SYMBOL     LOCATION      SYMBOL     LOCATION
   999        914           900        91D           901        927           920        932           911        944
   912        972           910        9A2           950        A6D

  *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,DECK,NOLOAD,MAP
  *OPTIONS IN EFFECT*  NAME = MAIN    , LINECNT =      60
  *STATISTICS*    SOURCE STATEMENTS =      74,PROGRAM SIZE =     4934
  *STATISTICS*  NO DIAGNOSTICS GENERATED
```

APPENDIX G

VEHICLE TEST DATA REPORTS

Because of the large number of test reports for different phases of the vehicle tests and subsequent collection of brake emissions, the individual data sheets were assembled into a separate volume for each vehicle test. The original test data sheets were retained by the Principal Investigator at Bendix Research Laboratories.

The volume for each vehicle test contains seven major sections, one for each test schedule; and each section is broken down further into three secondary sections for the vehicle operation results, the brake emissions data sheets, and the analytical results:

Vehicle operation data reports:

- Figure G-1 is the Vehicle Log Sheet which remained in the vehicle to record the overall vehicle operation throughout the test schedule.
- Figure G-2 is the Burnish report.
- Figure G-3 is the Detroit Traffic data sheet used during the Baseline and Detroit Traffic schedules.
- Figure G-4 is the 10-Stop Fade data sheet.
- Figure G-5 is the 15-Stop Fade data sheet.
- Figure G-6 is the Recovery data sheet used in conjunction with the 10- and 15-Stop Fade data sheets during the Fade schedules.
- Figure G-7 is the Reburnish data sheet used in the 10- and 15-Stop Fade schedules.

Brake Emissions data sheets:

- Figures G-8 and G-9 are the Wear Sheet-Front Axle and Wear Sheet-Rear Axle used to record both weight and thickness losses of all friction materials on the vehicle.
- Figures G-10 and G-11 are the Collection of Brake Emissions (Right Side) and Collection of Brake Emissions (Left/Control Side) which were used to record and calculate the brake wear debris collected in the sump, on the surfaces, and the airborne samples.
- Figure G-12 is the Test Summary Sheet used to summarize the wear data and to check out the material balances.

Analytical Results:

- Figure 8-13 is the Microscopy Count Sheet onto which each fiber found by microscopy was classified according to its dimensions.
- Figure 8-16 is the Computer Printout which gave the asbestos percent and the size distribution.
- Figure G-13 is the Asbestos Emission Summary Sheet used to summarize each test schedule.

VEHICLE LOG SHEET

Vehicle Test No. ______ Test Dates: Start: ________

Test Sequence: ________________ Finish: ________

DATE	AMB. (°F) AM/PM	WEATHER	ODOMETER			STOPS		COMMENTS
			START	FINNISH	TOTAL	PEDAL APPL.	COMPLETE	
TOTALS								

Figure G-1 - Vehicle Log Sheet

Test No. ____________

Burnish (Brake Performance Test Weight):

Odometer ____________ Date ____________ Temp. ____________

200 Stops, 40 MPH, 12 FPSPS in Highest Gear, 250° IBT or 1 Mile Maximum - 40 MPH Cooling Speed, 80% Burnish								
Stop	Initial Temperatures °F				Max. L.P. psi	Max. P.F. lb.	P.T. in.	Comments
	L.F.	R.F.	L.R.	R.R.				
1								
20								
40								
60								
80								
100								
120								
140								
160								
180								
200								

Comments

Figure G-2 - Burnish Report

DETROIT CITY TRAFFIC TEST

START ODOM._____	END ODOM.____	TEST NO._______	DATE_________

CAR NO.	TIME	AMB.	L.F.	R.F.	L.R.	R.R.	COMMENTS
START **							
MICH. & 3RD. **							
ADAMS & WOOD.							
ADAMS & WOOD.							
12 MILE **							
ADAMS & WOOD.							
ADAMS & WOOD.							
ADAMS & WOOD.							
12 MILE **							
ADAMS & WOOD.							
ADAMS & WOOD.							
ADAMS & WOOD.							
12 MILE **							
ADAMS & WOOD.							
ADAMS & WOOD.							
ADAMS & WOOD.							
12 MILE **							
ADAMS & WOOD.							
ADAMS & WOOD.							
ADAMS & WOOD.							
12 MILE **							
ADAMS & WOOD.							
ADAMS & WOOD.							
END **							

Figure G-3 - Detroit Traffic Data Sheet

Test No. ______________________

First Baseline: (Brake Performance Test Weight)

Odometer ______________ Date ______________ Temp. ______________

3 Stops, 30 MPH, 10 FPSPS in Highest Gear, 140°-150° IBT Each Stop										
Stop	Initial Temperatures °F				L.P.*PSI			Max. P.F. lb.	P.T. in.	Comments
	L.F.	R.F.	L.R.	R.R.	Init.	Sust.	Fin.			
1										
2										
3										

First Fade: Odometer ______________ Date ______________ Temp. ______________ Wind ______________

10 Stops, 60 MPH, 15 FPSPS in Highest Gear, 0.4 Mile Interval, 140°-150° IBT For Stop I Req't.: 200# Maximum P.E. First Four Stops												
Stop	Initial Temperatures °F**				L.P.*PSI			P.F. lb.			P.T. in.	Comments
	L.F.	R.F.	L.R.	R.R.	Init.	Sust.	Fin.	Init.	Sust.	Fin.		
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												

Total Elapsed Time ______________ Sec.

*Must include maximum line pressure.

**On cooling cycle.

Figure G-4 - 10-Stop Fade Data Sheet

Test No. ____________________

First Baseline: (Brake Performance Test Weight)

Odometer ____________ Date ____________ Temp. ____________

3 Stops, 30 MPH, 10 FPSPS in Gear, 140°-150° IBT Each Stop										
Stop	Initial Temperatures °F				L.P.*PSI			Max. P.F. lb.	P.T. in.	Comments
	L.F.	R.F.	L.R.	R.R.	Init.	Sust.	Fin.			
1										
2										
3										

First Fade: Odometer ____________ Date ____________ Temp. ____________ Wind ____________

15 Stops, 60 MPH, 15 FPSPS in Gear, 0.4 Mile Interval, 140°-150° IBT For First Stop Req't.: 200# Maximum P.E. For First Eight Stops												
Stop	Initial Temperatures °F				L.P.*PSI			P.F. lb			P.T. in.	Comments
	L.F.	R.F.	L.R.	R.R.	Init.	Sust.	Fin.	Init.	Sust.	Fin.		
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												
13												
14												
15												

Total Elapsed Time Sec.

*Must include maximum line pressure.

Figure G-5 - 15-Stop Fade Data Sheet

Test No. ____________

Recovery - One Mile After Last Fade Stop, at 40 MPH Cooling Speed

12 Stops, 30 MPH, 10 FPSPS in Highest Gear, or Max. Decel. for 200 lb. PF if 10 FPSPS Cannot Be Obtained, One Mile Interval
Req't.: 5 FPSPS Minimum for 200# P.E. for First 5 Stops, 150# Maximum P.E. for Stop #6

Stop	Initial Temperatures °F				L.P.*PSI			P.F. lb.			P.T. in.	Comments
	L.F.	R.F.	L.R.	R.R.	Init.	Sust.	Fin.	Init.	Sust.	Fin.		
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												

Driver ______________________ Observer ______________________

(1) If warning light is activated, which M'cyl. piston bottomed out? Front ☐ Rear ☐
(2) Center differential valve piston.
(3) Check front/rear pressure differential:
Front line pressure ______ PSI
Rear line pressure ______ PSI
Read simultaneously at approx. 1000 PSI

Figure G-6 - Recovery Data Sheet

Reburnish (Brake Performance Test Weight);

Odometer ____________________ Date ____________________ Temp. ____________________

35 Stops, 40 MPH, 12 FPSPS, 250° IBT of One Mile Maximum in Gear								
Stop	Initial Temperatures °F				Max. L.P. psi	Max. P.F. lb.	P.T. in.	Comments
	L.F.	R.F.	L.R.	R.R.				
1								
10								
20								
25								
35								

Figure G-7 - Reburnish Data Sheet

Vehicle Test No. ____________

Test Sequence: ______________

WEAR SHEET _________ AXLE

MAKE OF CAR: __________________________________ MODEL: ____________________________________

LINING: ____

COMMENTS: ____

RIGHT ____________										
Date	Mileage	Total Stops	1	2	3	4	5	6		Weight Loss

RIGHT ____________										
Date	Mileage	Total Stops	1	2	3	4	5	6	7	Weight Loss

LEFT ____________										
Date	Mileage	Total Stops	1	2	3	4	5	6		Weight Loss

LEFT ____________										
Date	Mileage	Total Stops	1	2	3	4	5	6	7	Weight Loss

Figure G-8 - Wear Sheet - Front Axle

Vehicle Test No.________

Test Sequence:________

WEAR SHEET ____________ AXLE

MAKE OF CAR: ______________________________ MODEL: ______________________________

LINING: ____

COMMENTS: ____

RIGHT ________ BRAKE (PRI. OR FORWARD)

Date	Mileage	Total Stops	1	2	3	4	5	6	Weight Loss

RIGHT ________ BRAKE (SEC. OR REVERSE)

Date	Mileage	Total Stops	1	2	3	4	5	6	7	8	Weight Loss

LEFT ________ BRAKE (PRI. OR FORWARD)

Date	Mileage	Total Stops	1	2	3	4	5	6	Weight Loss

LEFT ________ BRAKE (SEC. OR REVERSE)

Date	Mileage	Total Stops	1	2	3	4	5	6	7	8	Weight Loss

Figure G-9 - Wear Sheet - Rear Axle

COllECTION OF BRAKE EMISSIONS (RIGHT SIDE)

Vehicle Test No. ______ Test Dates Start: ________
Test Sequence: ________________ Finish: ________

RIGHT FRONT BRAKE

SUMP SAMPLE: filter+debris:
·Caliper Piston filter: ________
·Rivet Holes gm

SURFACES SAMPLE: filter+debris:
·Shroud + Rotor filter: ________
·Backing Plate gm

AIRBORNE SAMPLE:

filter + debris

total on 8.0µ
total on 0.2µ
total on filters: gm

TOTAL SAMPLE:
SUMP:
SURFACES:
AIRBORNE: ________ gm

COMMENTS:

RIGHT DRUM BRAKE

SUMP SAMPLE: filter+debris:
·Wear Track 2 filters: ________
·Rivet Holes total: gm
-80% Return: ________
20% Retain: gm

Corrected Sump Sample Weight
This test·
Previous test · ________

SURFACES SAMPLE: filter+debris:
·Brake Pads filter: ________
·Drum gm

TOTAL SAMPLE:
Sump:
SURFACES:
AIRBORNE: ________ gm

AIRBORNE SAMPLE:

	8.0µ	0.2µ
filter + debris:		
filter:	________	________
total on 8.0µ:		
total on 0.2µ:	________	
total on filter: gm		

COMMENTS:

Figure G-10 – Collection of Brake Emissions (Right Side)

COLLECTION OF BRAKE EMISSIONS (LEFT SIDE)

Vehicle Test No. ____
Test Sequence: ________________

LEFT FRONT BRAKE

SUMP SAMPLE: filter+debris:
· Caliper Piston filter: ________
· Rivet Holes gm

SURFACE SAMPLE: filter+debris:
· Shroud + Rotor filter: ________
· Backing Plate gm

TOTAL SAMPLE:
→ SUMP:
→ SURFACES: ________ gm

COMMENTS:

LEFT DRUM BRAKE

SUMP SAMPLE: filter+debris:
· Wear Track 2 filters: ________
· Rivet Holes gm
-80% return:
20% retain: gm

Corrected Sump Sample Weight
→ This test:
Previous Test: ________ gm

TOTAL SAMPLE:
→ SUMP:
→ SURFACES:

SURFACES SAMPLE: filter+debris:
· Brake Ports filter: ________
· Drum gm

COMMENTS:

CLUTCH

	8.0 μ	0.2 μ
filter+debris:		
filter:	________	________
total on 8.0:		
total on 0.2:	________	
total on filters:		

Figure G-11 - Collection of Brake Emissions (Left Side)

TEST SUMMARY SHEET

Vehicle Test No. ____ Test Dates: Start: ________

Test Sequence __________________ Finish: ________

Miles:

Pedal Applications:

Complete Stops:

Comments:

FRONT DISC BRAKES:	RIGHT/SHROUDED	LEFT/CONTROL	DIFF
Temperature Range (°F):			
Samples Collected (gms):			
Sump:			
Surfaces:			
Airborne:			
Total:			
Lining Wear: I/o			
Total			
(Recovery %)			
REAR DRUM BRAKES:			
Temperature Range (°F):			
Samples Collected (gms):			
Sump:			
Surfaces:			
Airborne:			
Total:			
Lining Wear: P/S			
Total			
(Recovery %)			
CLUTCH:			
Samples Collected (gms.)			

Figure G-12 - Test Summary Sheet

Asbestos Emissions Summary Sheet

Vehicle Test No. _____
Test Schedule : _______________

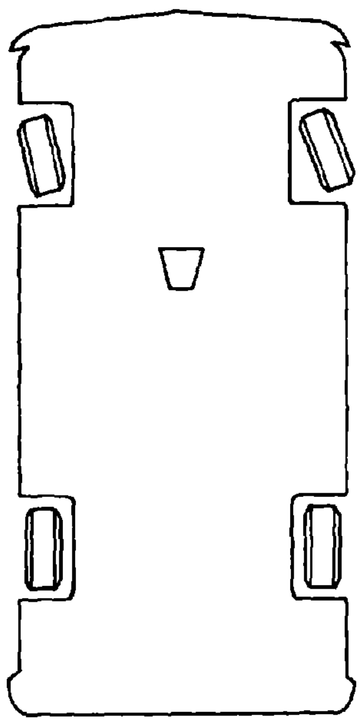
(Note: Debris data are reported as Debris generated per stop)

RIGHT FRONT BRAKE:

Sump:
Debris:
Asbestos:

Surfaces:
Debris:
Asbestos:

Airborne:
Debris:
Asbestos:



CLUTCH:
Debris: mg
Asbestos: %

RIGHT REAR BRAKE:

Sump:
Debris:
Asbestos:

LEFT REAR BRAKE

Surfaces:
Debris:
Asbestos:

Airborne
Debris:
Asbestos:

Figure G-13 - Asbestos Emissions Summary Sheet

APPENDIX H

ASBESTOS EMISSIONS ANALYSIS REPORTS FROM BATTELLE COLUMBUS LABORATORIES AND JOHNS-MANVILLE RESEARCH AND ENGINEERING CENTER

The following information has been excerpted from the final summary report "Asbestos Emissions Analysis" by Battelle Columbus Laboratories (C. W. Melton and W. M. Henry) to the Environmental Protection Agency (Contract No. 68-01-0416). Dr. Joseph H. Somers was the Project Technical Officer who supplied this information to Bendix Research Laboratories.

The objective of the project was to analyze 24 clutch and brake lining emissions for asbestos content. The samples were generated, collected, and submitted for analysis by the Bendix Research Laboratories.

The analytical method used for asbestos in brake and clutch lining emissions was a modification of one developed for the analysis of asbestos in collections of airborne particulate. In general, results indicated that sump samples contained, by far, more asbestos than airborne or surface samples.

Experimental Procedure and Calculations:

The analytical procedure employed was as follows:

(1) An aliquot of the brake or clutch debris was weighed.

(2) The aliquot was put into a centrifuge tube and was low-temperature ashed for three days.

(3) The ash residue was suspended in 10 ml of an aqueous solution to which 3 drops of 1.0 percent Aerosol OT was added and then was treated ultrasonically to separate the asbestos fibers into colloidal fibrils.

(4) The extraneous material was separated by centrifugation from the asbestos which remained in colloidal suspension in the supernatant liquid.

(5) The supernatant liquid was filtered through a Millipore filter (HAWP 025, HA 0.45 μ, 25 mm) to deposit the asbestos fibrils uniformly over the surface of the filter.

(6) A carbon film was vapor-deposited over the asbestos fibrils on the filter and a 3-mm x 3-mm square was cut from the resulting carbon-coated specimen.

(7) The filter was dissolved in acetone to leave the carbon film bearing the asbestos fibrils.

(8) The carbon film was picked up on a 200-mesh electron microscope specimen support grid.

(9) The support grid and carbon film were loaded into the transmission electron microscope and the fibrils within several (usually ten) grid openings were counted and the results recorded as number of fibrils per grid opening.

(10) The number of fibrils per grid opening was translated into micrograms of asbestos in the aliquot taken by using a standard curve which was generated from known standard samples.

(11) Percentage asbestos in the sample was calculated by dividing the weight of the detected asbestos by the weight of the aliquot.

Experimental Results

Results of the analyses of the 24 samples submitted by Bendix are as follows:

BATTELLE SAMPLE NO.	BENDIX SAMPLE DESCRIPTION	PERCENT ASBESTOS IN SAMPLE
29897-1-1	Vehicle Test 1 Detroit Traffic Schedule Right Front Brake Airborne Sample	0.00055
29897-1-2	Vehicle Test 1 Detroit Traffic Schedule Right Rear Brake Airborne Sample	0.00057
29897-1-3	Vehicle Test 1 Detroit Traffic Schedule Right Front Brake Sump Sample	0.207
29897-1-4	Vehicle Test 1 Detroit Traffic Schedule Clutch Airborne Sample	0.0068
29897-1-5	Vehicle Test 1 Detroit Traffic Schedule Right Rear Brake Surfaces Sample	0.0061
29897-1-6	Vehicle Test 1 Detroit Traffic Schedule Right Rear Brake Sump Sample	0.025
29897-8-1	Vehicle Test 1 10-Stop Fade Right Front Brake Airborne Sample	0.031
29897-8-2	Vehicle Test 1 10-Stop Fade Right Front Brake Sump Sample	1.22

BATTELLE SAMPLE NO.	BENDIX SAMPLE DESCRIPTION	PERCENT ASBESTOS IN SAMPLE
29897-8-3	Vehicle Test 1 10-Stop Fade Right Rear Brake Airborne Sample	0.0074
29897-8-4	Vehicle Test 1 10-Stop Fade Right Rear Brake Sump Sample	0.216
29897-8-5	Vehicle Test 2 Burnish Schedule Right Front Brake Sump Sample	0.275
29897-8-6	Vehicle Test 2 Burnish Schedule Right Rear Brake Sump Sample	0.103
29897-8-7	Vehicle Test 2 Burnish Schedule Right Front Brake Airborne Sample	0.100
29897-8-8	Vehicle Test 2 Burnish Schedule Right Rear Brake Surfaces Sample	0.376
29897-14-1	Vehicle Test 1 Detroit Traffic Schedule Right Front Brake Surfaces Sample	0.011
29897-14-2	Vehicle Test 2 Detroit Traffic Schedule Right Front Brake Airborne Sample	0.0057
29897-14-3	Vehicle Test 2 Detroit Traffic Schedule Right Front Brake Sump Sample	0.62

BATTELLE SAMPLE NO.	BENDIX SAMPLE DESCRIPTION	PERCENT ASBESTOS IN SAMPLE
29897-14-4	Vehicle Test 2 Detroit Traffic Schedule Right Rear Brake Airborne Sample	0.015
29897-14-5	Vehicle Test 2 Detroit Traffic Schedule Right Rear Brake Sump Surface	0.057
29897-14-6	Vehicle Test 2 Detroit Traffic Schedule Right Rear Brake Surfaces Sample	0.061
29897-14-7	Vehicle Test 3 Detroit Traffic Schedule Right Front Brake Airborne Sample	0.016
29897-14-8	Vehicle Test 3 Detroit Traffic Schedule Right Front Brake Sump Sample	0.135
29897-14-9	Vehicle Test 3 Detroit Traffic Schedule Right Rear Brake Airborne Sample	0.044
29897-14-10	Vehicle Test 3 Detroit Traffic Schedule Right Rear Brake Sump Sample	0.0104

Johns-Manville

Research & Engineering Center

P. O. Box 159
Manville, N. J. 08835
(201) 722-9000

September 6, 1972

Dr. M. G. Jacko
Materials and Processes Department
Bendix Research Laboratories
Southfield, MI 48075

Dear Dr. Jacko:

We have finally completed the analysis of the brake lining wear debris you sent to us. These samples were described as follows in your letter to Dr. Speil of July 5, 1972.

Sample No. 1 - Vehicle Test 1
J-M No. 4123-58-1 Detroit Traffic Schedule
Right Front Brake
Surfaces Sample

Sample No. 2 - Vehicle Test 1
J-M No. 4123-58-2 Detroit Traffic Schedule
Right Rear Brake
Surfaces Sample

Sample No. 3 - Vehicle Test 1
J-M No. 4123-58-3 Detroit Traffic Schedule
Right Rear Brake
Airborne Sample

The fiber content of the samples and the weight loss on ignition are given below. The fiber content was determined by the rub-out procedure which I believe we explained to you at the time of your visit to our laboratory.

	No. 1	No. 2	No. 3
Initial Sample Weight (mg)	50.78	46.50	45.70
Weight of Ash After Ignition @ 400C(mg)	43.50	31.10	30.20
Weight Loss on Ignition	14.4%	33.1%	33.9%
Total Fiber in Sample (micrograms)	2.54	0.98	2.73
Percent Fiber in Original Sample	0.005	0.002	0.006

We were unable to determine the element distribution because our emission spectrograph has been disassembled for our move to Denver.

If you have any questions regarding these samples or procedures you can contact Dr. Speil. He will be available through the month of September. After that time you can contact me in Denver. Our mailing address and telephone number in Denver will be:

Johns-Manville Corporation
P. O. Box 5108
Denver, Colorado 80217

Phone: (303) 770-1000

Very truly yours,

J. P. Leineweber

J. P. Leineweber

mp

cc: Dr. S. Speil

Table 8-1 - Comparison of Disc Brake Versus Drum Brake Operating Conditions

Parameter	Disc	Drum
Type of system	Open	Closed
Air flow	High	Low
Emissions	Relatively few trapped	Much trapped in surfaces and in sump
Third-body abrasive wear	Relatively none	Some

P-82-99-3

Table 8-2 - Samples Produced by Brake Emissions Collection

Sample	Disc Brake	Drum Brake
Sump	Trapped debris* - includes that in rivet holes, on pads and in caliper piston	Trapped debris* - includes that in rivet holes, on linings, and on drum surface+ +Provides third-body wear
Surfaces	Accumulated on shroud - normally road dropout	Accumulated on brake surfaces*
Airborne	Airborne samples collected on filters	Airborne samples collected on filters

P-82-99-3

*Normally not completely released during brake operation. (This may be a "controllable" material which could be disposed of properly).

8.0μ and 0.2μ Nuclepore filter train). The contract did not require Bendix Research Laboratories to sample the left front disc brake; however, some samples were taken so that it would be possible to assess the quantity of material remaining in an OEM configuration disc brake. These data were prepared for Section 9.

8.2.3 Drum Brake Samples

In all cases, three samples were obtained from the right rear drum brake collector: sump sample (including debris in rivet holes, on lining surfaces, and on drum rubbing surface), wear debris which remains in the brake; surfaces sample (including all other debris remaining in the brake collector and on the brake surfaces); and the airborne sample (debris collected on 8.0μ and 0.2μ Nuclepore filter train). The contract required that selected left rear drum brake samples be taken in order to assess the quantity of material remaining in an OEM configuration drum brake. These data were prepared for Section 9.

8.2.4 Clutch Samples

Since the airborne samples taken from the clutch for vehicle test 1 were extremely small compared to the corresponding airborne samples from the brakes, it was decided to accumulate the entire sump and surfaces samples for all three vehicle tests. These data were prepared for Section 9.

8.2.5 Improved Friction Material Weighing Procedure

The original equipment drum brake linings and disc brake pads were riveted to their corresponding brake shoes. The weight of the metallic shoe placed the combined weights in excess of 400 gm; the weight could then be recorded to the nearest 0.1 gm. The anticipated weight differences of approximately 0.5 gm would have had less than desired accuracy. By removing the rivets, the weights of the friction materials alone could be determined. Since all friction material weights were less than 200 gms in this condition, weighing on an analytical balance was possible. After the friction materials were dried in a vacuum oven at 90°C, the weights were recorded to the nearest 0.01 gm, giving the desired accuracy. The linings were then refastened to the shoes by flat head nuts and bolts for vehicle installation and testing.

8.3 ANALYTICAL PROBLEM DEFINITION

8.3.1 Composition of Wear Debris

The brake converts the kinetic energy of the moving vehicle into heat, absorbs the heat, and eventually dissipates it to the atmosphere. As a result of the energy conversion at the stator-rotor interface, the compositions and microstructures of the brake lining and rotor surfaces are altered.